Parameterization of non orographic gravity waves in large scale models
Formalism, Impacts, and test against observations

François Lott,

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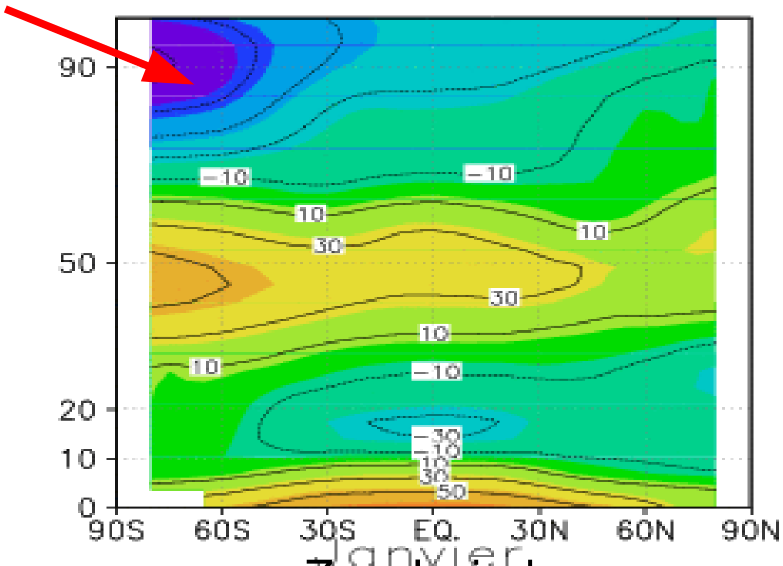
1) Impact of gravity waves on the middle atmosphere climate
2) Spectral parameterizations and impact
3) Multiwave stochastic parameterizations
   and application to convective gravity waves
4) Application to gravity waves generated by fronts
5) Validation against balloon observations
6) Perspective

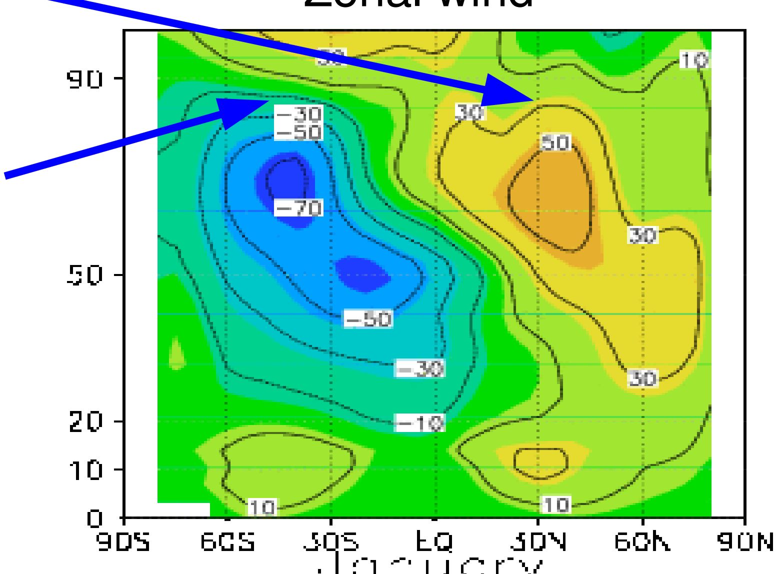
Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

The need to parameterize a broad spectrum of waves: minima of T at the summer mesopause, and closure of the jets an the midlatitudes mesopause (see textbooks, Andrew et al.~1987)

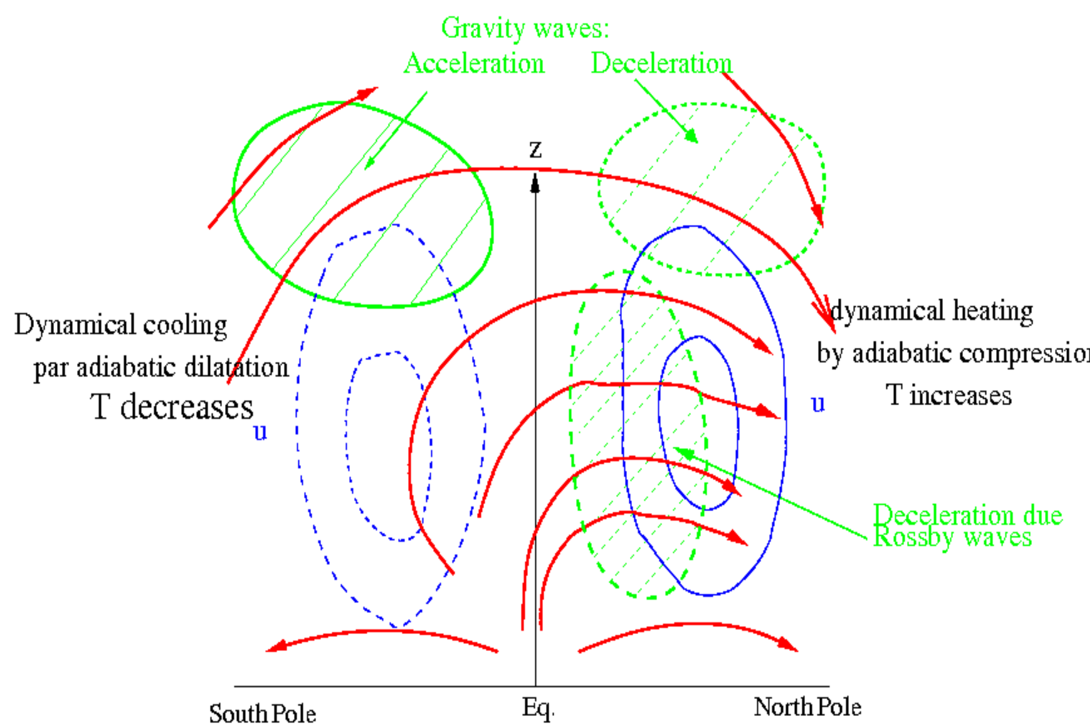
January Temperatures



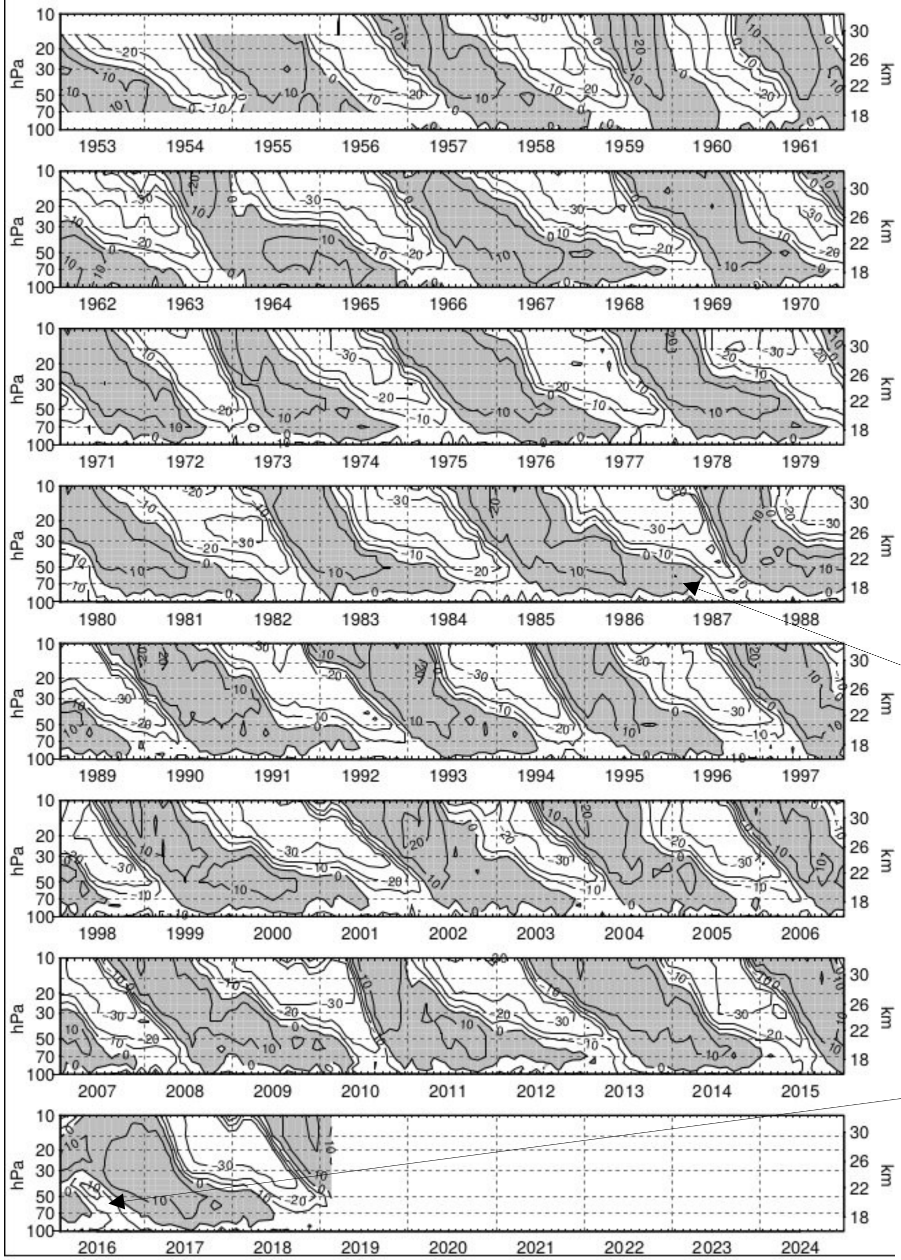
Zonal wind



The meridional circulation driven by waves and the « downward control » (review in Haynes et al.~1991)



Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate



Quasi biennial oscillation

of thezonal mean zonal wind at the equator,

$$\overline{u}(t, 0, z)$$

Radiosonde observations at Singapour since 1952

Aperiodic decent of zonal mean zonal Winds (mean period 27.5 month)

Stalling of the westerlies near above the tropopause

Not well reproduce in models around 100hPa

Recent disruptions that may be caused by the changing climate

See QBO Initiative

Butchart et al. (GMD 2017)

Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

Plumb (1977)'s model with 2 GWs interacting with the zonal wind:

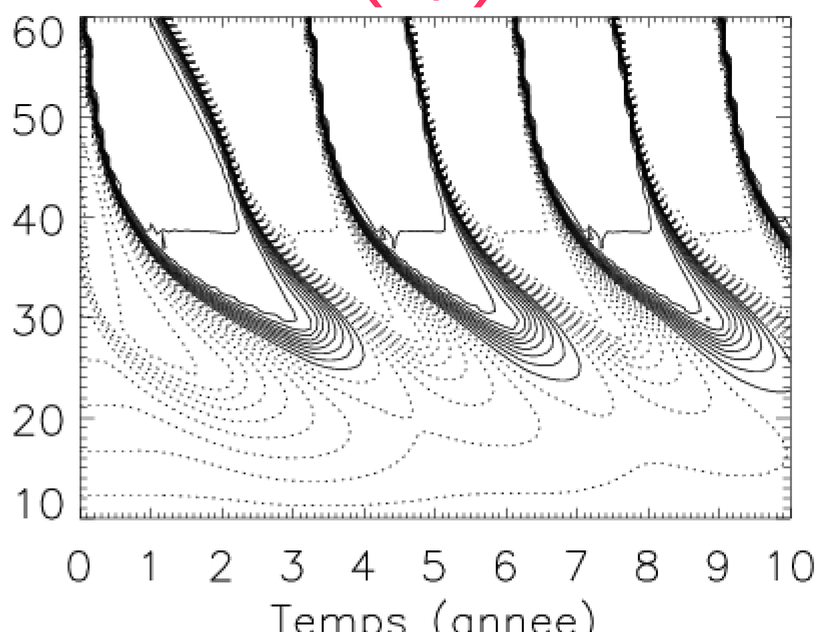
$$\frac{\partial \overline{u}}{\partial t}=\sum_{i=1}^{2}\frac{\partial \overline{F}_i^z}{\partial z}+\nu\frac{\partial^2 \overline{u}}{\partial z^2}$$

F momentum flux of a single wave
(planetary or gravity)
(explicit or parameterized)

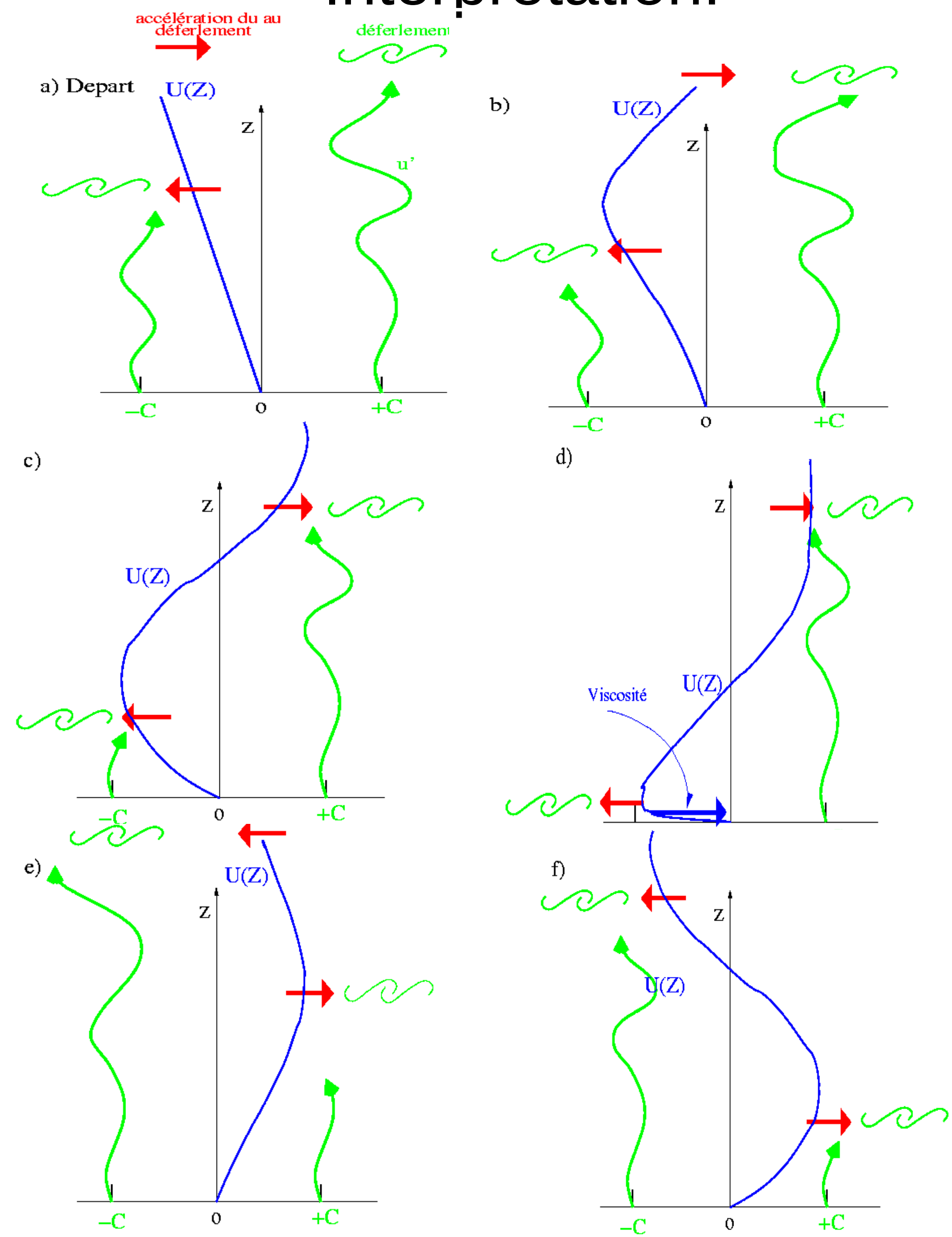
$$\overline{F}_i=\overline{\rho u' w'}_i$$

Result from the theoretical model:

$\overline{u}(z,t)$



Interpretation:



Parameterization of GWs in large scale models
2) Spectral parameterization and impact

Subgrid scale parametrizations are based on Fourier series decomposition of the waves field over the model gridbox of sizes δx, δy, and δt (δt can be larger than the model time-step).

$$w' = \sum_a \sum_b \sum_c \hat{w}(k_a, l_b, \omega_c) e^{i(k_a x + l_b y - \omega_c t)}$$

a, b, c are integers, (dropped in the following) and

$$k_a = a\frac{2\pi}{\delta x}, l_b = b\frac{2\pi}{\delta y}, \omega_c = c\frac{2\pi}{\delta t}$$

Since a lot of waves with different caracteristics are needed this triple Fourier series can be very expensive to evaluate each timestep

Multiwaves schemes:

Garcia et al. (2007),
Alexander and Dunkerton (1999)
Treat the large ensemble of waves but each quite independently from the others and using Lindzen (1981) to evaluate the breaking.

Globally spectral schemes:

Treat the spectra globally, and using analytical integrals of its different parts

Hine (1997),
Manzini and McFarlane (1997)

Warner and McIntyre (2001)

Parameterization of GWs in large scale models
2) Spectral parametrizations and impact

Globally spectral schemes,

Use that the observed GWs vertical (m-)spectra have a quasi-universal shape, with a m^{-3} slope for the $m>m^*$ part of the spectra that correspond to breaking waves

The **Warner and McIntyre (2001)** scheme propagate initial gravity wave spectra according to wave action conservation rules and troncate the propagated when it exceeds the m^{-3} saturated spectra to fit observed spectra

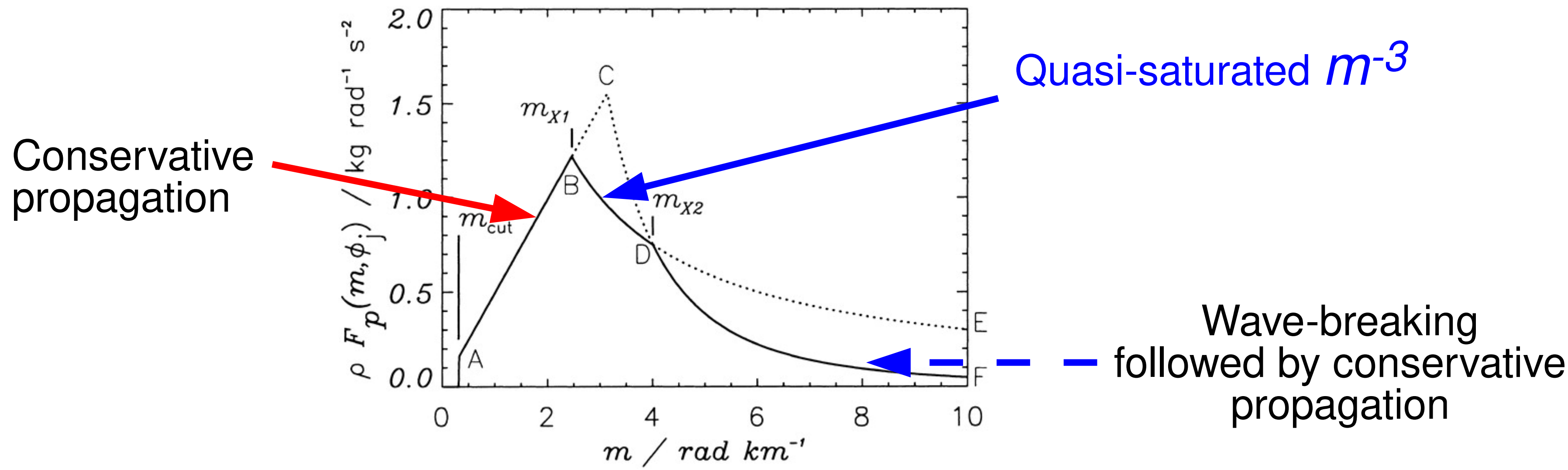


Fig. 1, from Warner and McIntyre (2001)

Parameterization of GWs in large scale models
2) Spectral parametrizations and impact

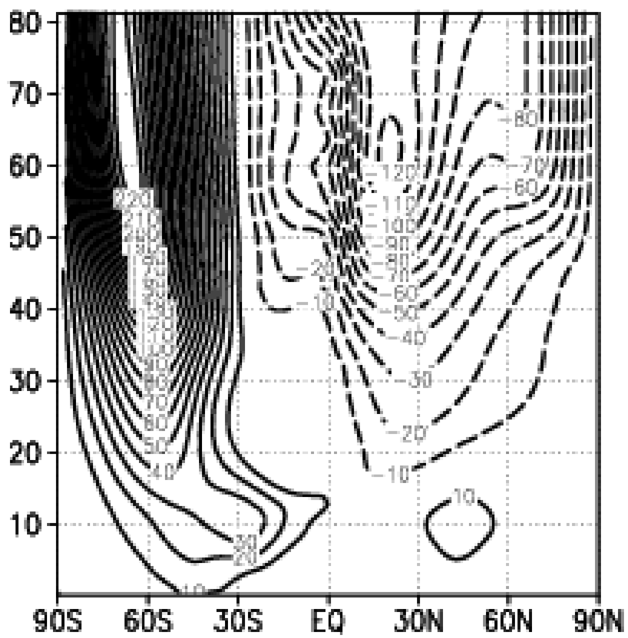
The effect of gravity waves can be well seen in the mesosphere
if we compare simulations with and without parameterization LMDz
(Lott et al. 2005, Lott and Millet 2010).
Here are used the Hines' scheme developped by Manzini et al.(1997) and
the Lott and Miller (1997) orographic scheme.

without

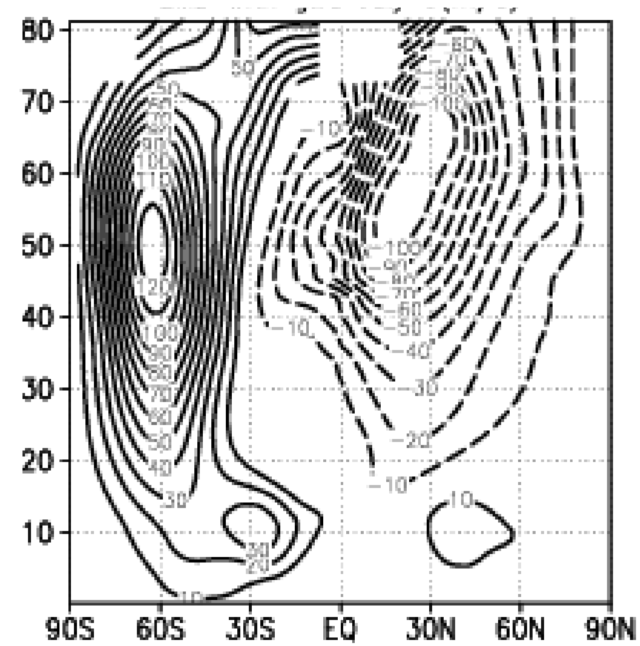
$$\bar{u} = \frac{1}{2\pi}\int_0^{2\pi} u\, d\lambda$$

with

July



July



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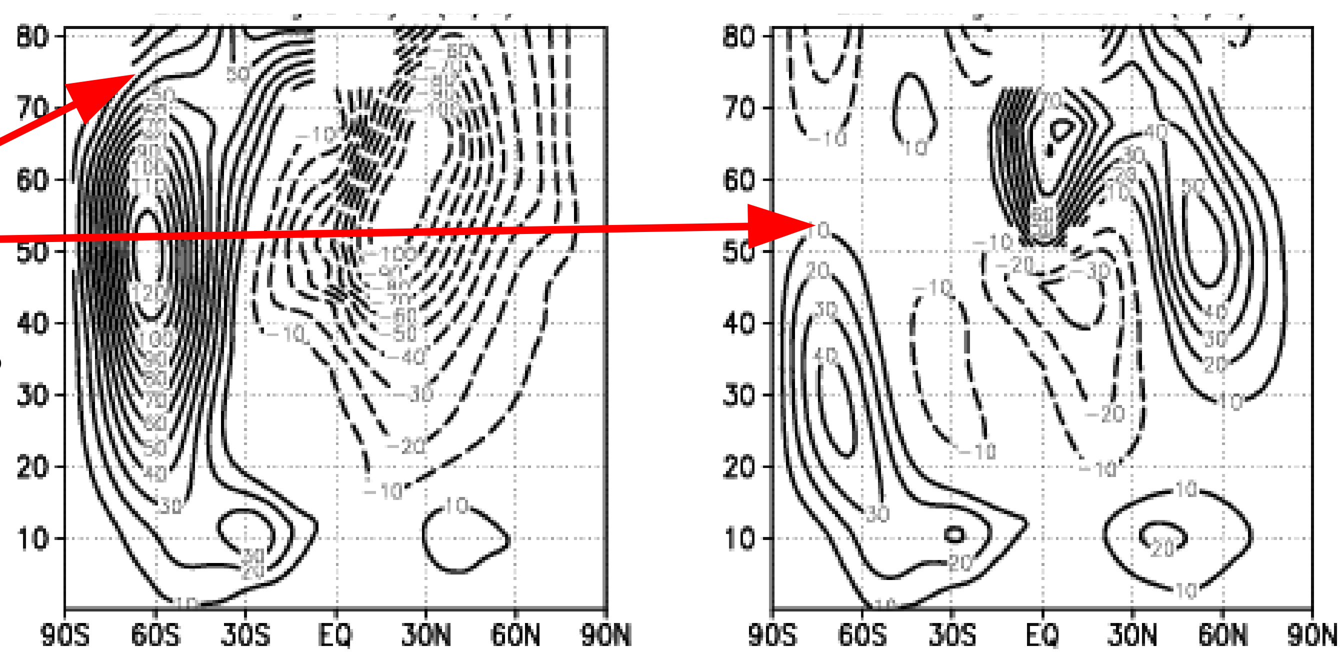
$$\bar{u} = \frac{1}{2\pi} \int_0^{2\pi} u \, d\lambda$$

July **October**

Descend of the

$\bar{u} = 0$

Line.



Date when it arrives
At 10hPa :
Final warming

Systematic Error !

Parameterization of GWs in large scale models
3) Multiwave stochastic param. and application to convective GWs

Exemple of the stochastic and « Multiwave » convective gravity wave scheme used in LMDz6 / IPSLCM6 model [Lott Guez and Maury GRL, 2012, Lott and Guez 2013]

Stochastic series with intermittency coefficients A_n's :

$$w' = \sum_{n=1}^{\infty} A_n \; \hat{w}_n(z) e^{z/2H} e^{i(k_n(x - C_n t))} \qquad \sum_{n=1}^{\infty} A_n^2 = 1$$

k_n, c_n chosen randomly, tunable parameter : $\mathbf{C_0}$ characteristic intrinsic phase speed

Launched flux :

$$\rho \hat{w}_n \hat{u}_n^*(z_l) \approx \rho_r \frac{\vec{k}_n}{|\vec{k}_n|} \exp(-m_{nl}^2 \Delta z^2) \; G_{uw} \; P_r^2$$

Pr : gridsccale precipitation

Δz : Source depth

G_{uw} : amplitude parameter

$\mathbf{Z_l}$: Launching altitude

Saturation criteria (dynamical filtering):

$$|\rho \hat{w}_n \hat{u}_n^*| \leq \rho_r S_c^2 |c_n - U(z)|^3 \frac{k_m}{N |k_n|^3}$$

$\mathbf{S_c}$: Saturation parameter

Online results with LMDz

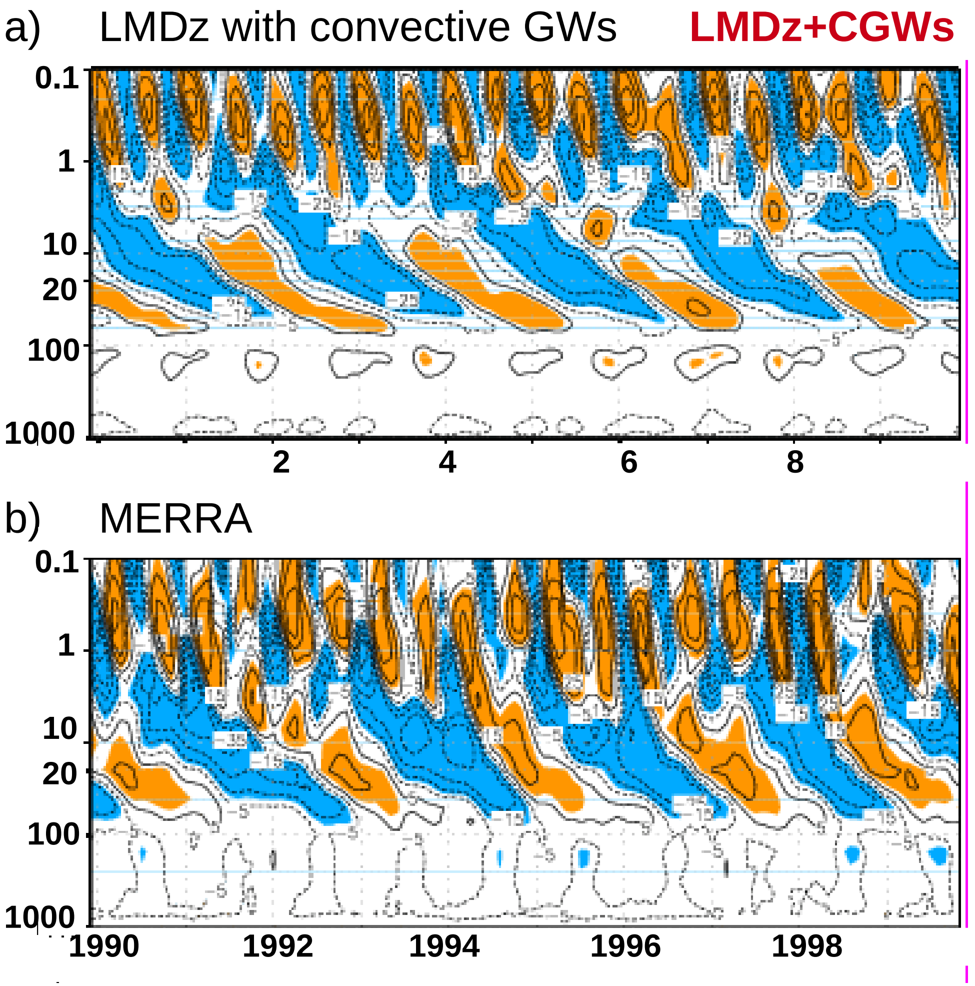
LMDz version with 80 levels, dz<1km
In the stratosphere

QBO of irregular
period with mean
around 26month,

20% too small amplitude

Systematic Error :
To small amplitude westerlies near
Above 100hPa
(Problem : this is probably the altitude
At which the QBO correlated with
the midllatitudes

(Anstey et al. 2021,
The Holton-Tan (1980) effect)



Lott and Guez, JGR13

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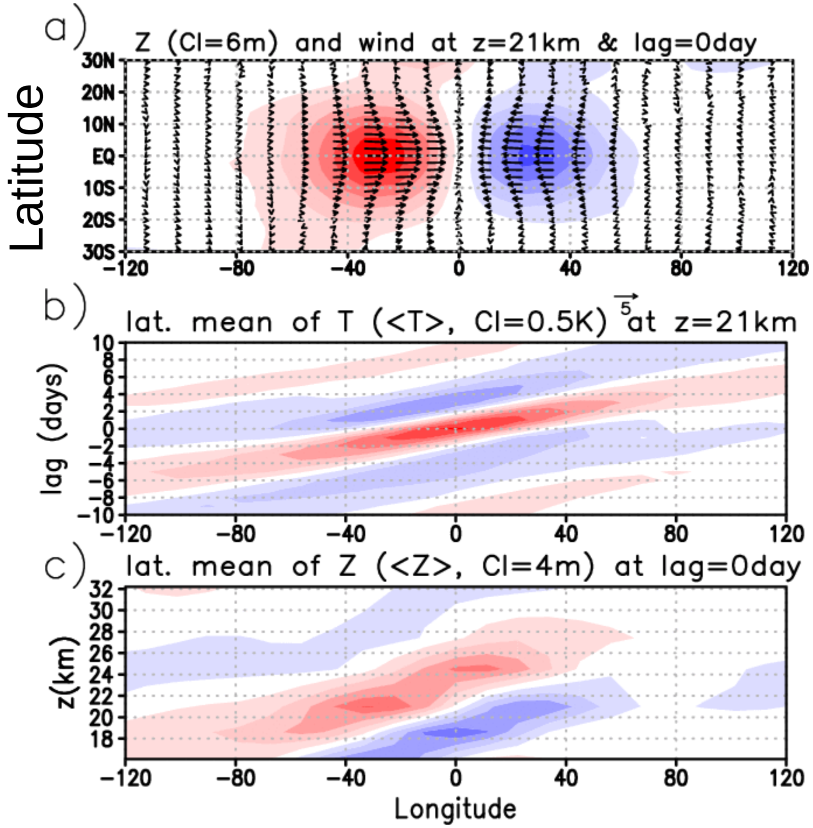
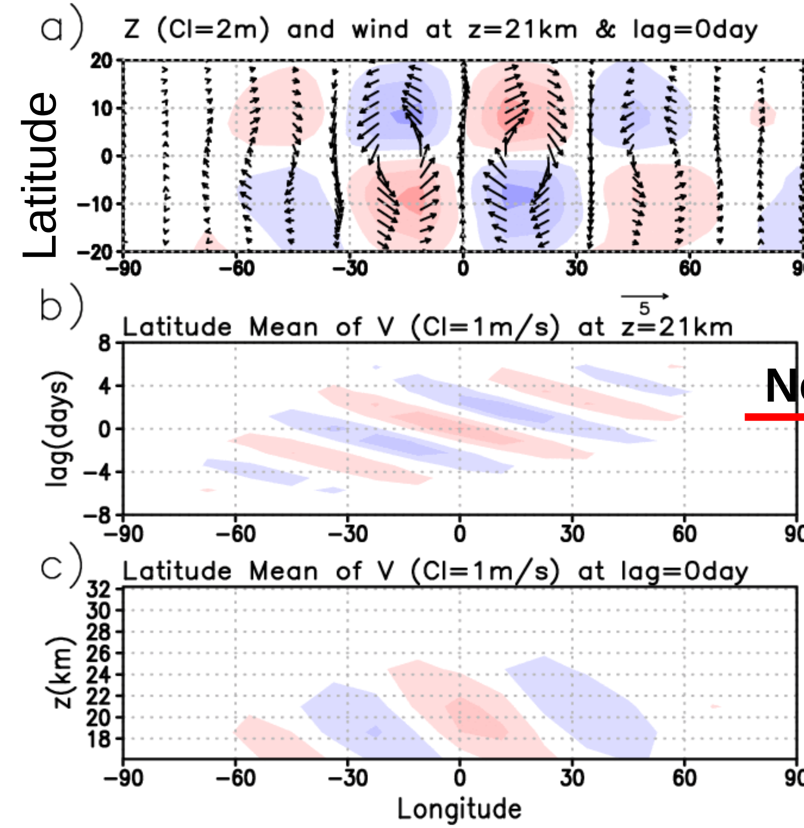
Kelvin wave composites



a) Pressure and wind structure at 21 km
b) Eastward propagation
c) Phase lines inclined eastward with altitude: upward propagation

Rossby gravity wave composites



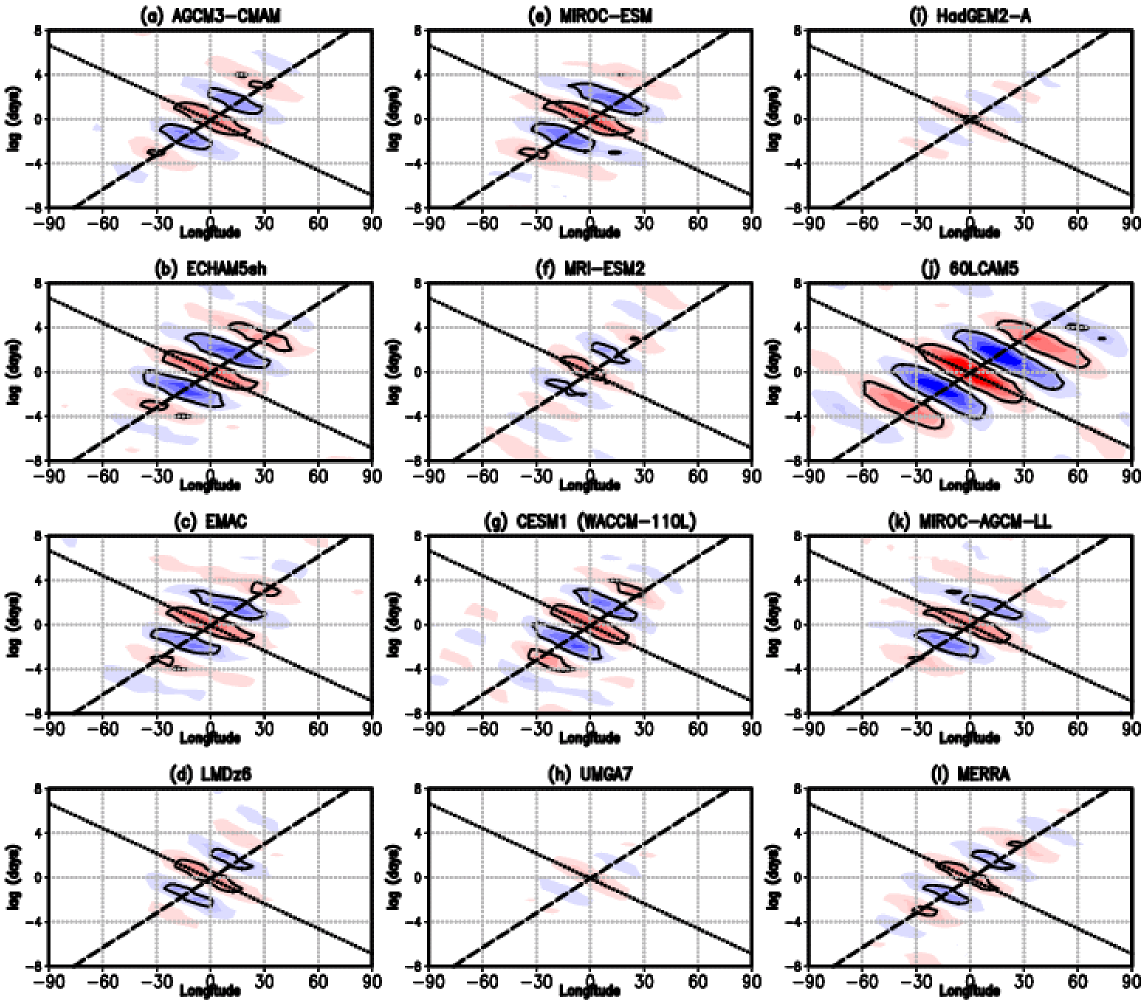
Next page

b) Westward phase speed eastward group speed
c) Phase lines inclined westward with altitude : upward propagation

Extraction of equatorial waves in reanalysis (for instance MERRA) and models :
Lott Kuttipurath and Vial (JAS 2007) ; Lott et al.~(JGR 2014)

Parameterization of GWs in large scale models
3) Multiwave stochastic param. and application to convective GWs

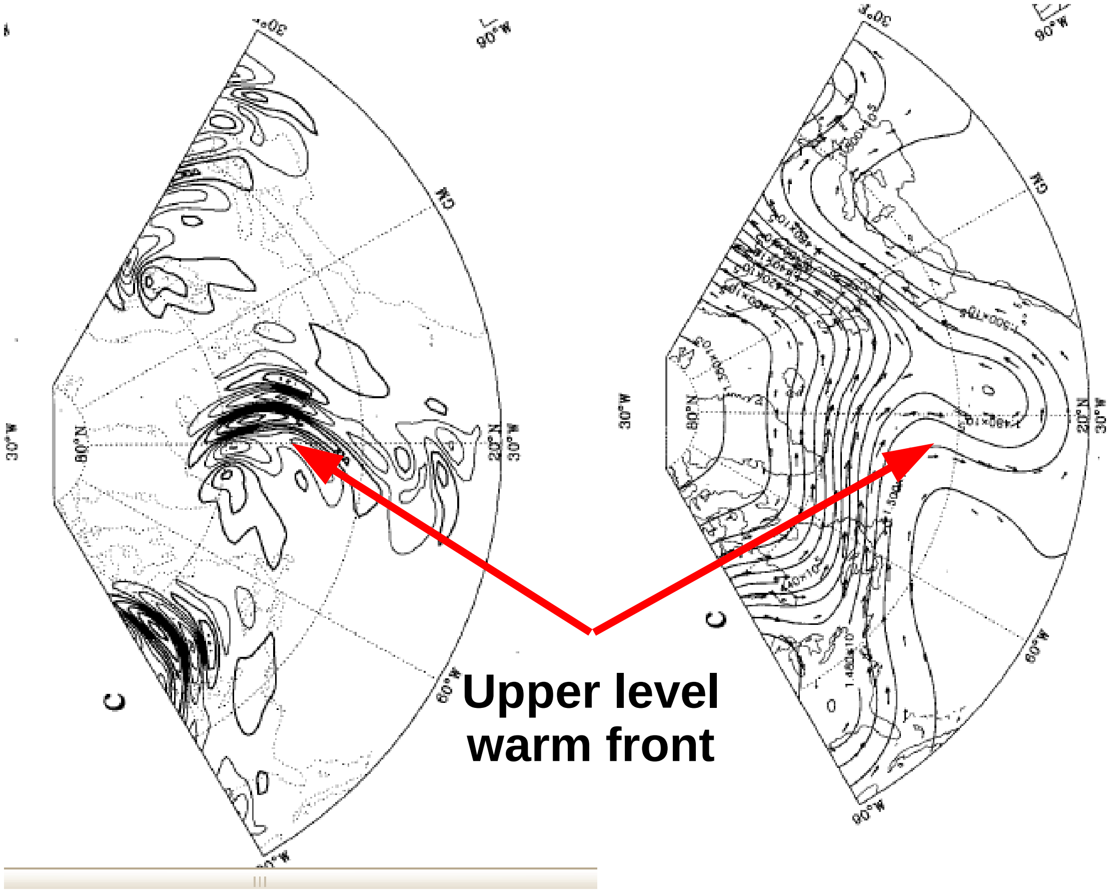
Rossby-gravity waves in 11 climate models+reanalysis participating to QBOi



Holt, L. Lott, F. and coauthors, QJRMS 2021

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Simulations to support these parameterizations:



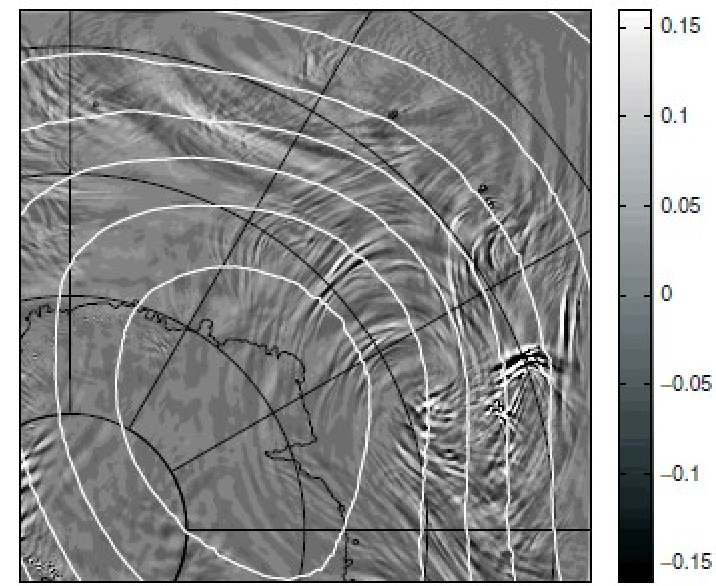


Figure 16. As Figure 2(b), but from a simulation with doubled horizontal resolution ($\Delta x = 10$ km).

Results confirmed by much higher resolution simulations

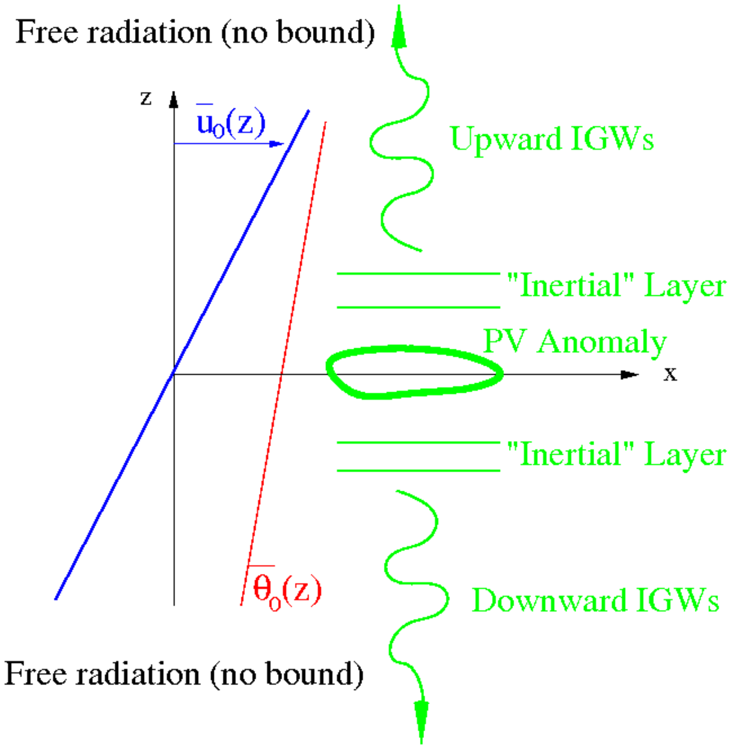
O'Sullivan and Dunkerton (1995)

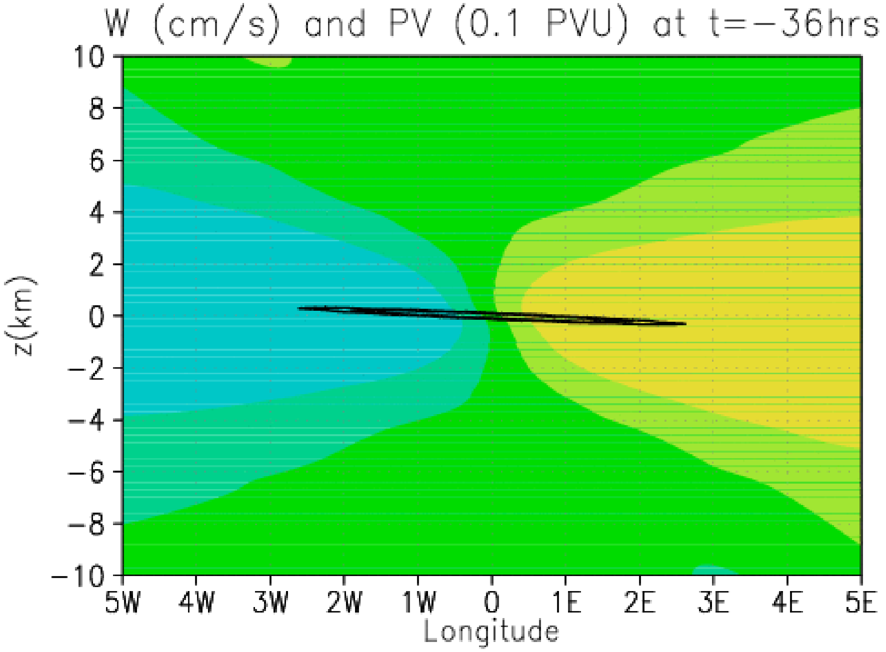
Plougonven Hertzog and Guez (2012)

This is somehow related to the "Geostrophic Adjustment" process.
Part of It, the so-called «Spontaneous adjustment» where a well-balanced flow radiates Gws can be handled analytically
Lott, Plougonven, Vanneste (2010, 2012)

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

<u>General setup:</u> A 3D (x,y,z) PV anomaly advected in a rotating (*f* =cte), stratified (BV freq ***N*=cte**) shear flow (vertical shear ***Λ*=cte**).





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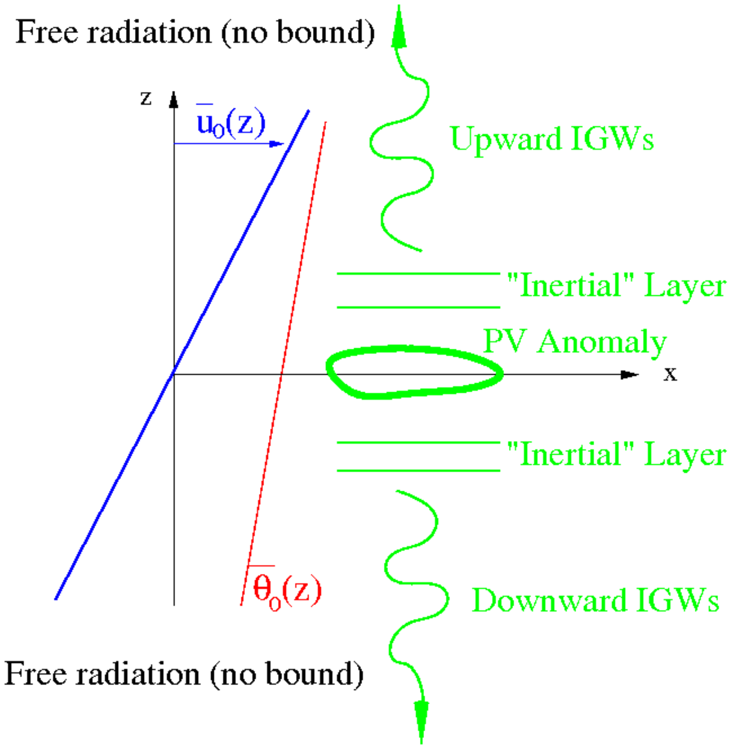

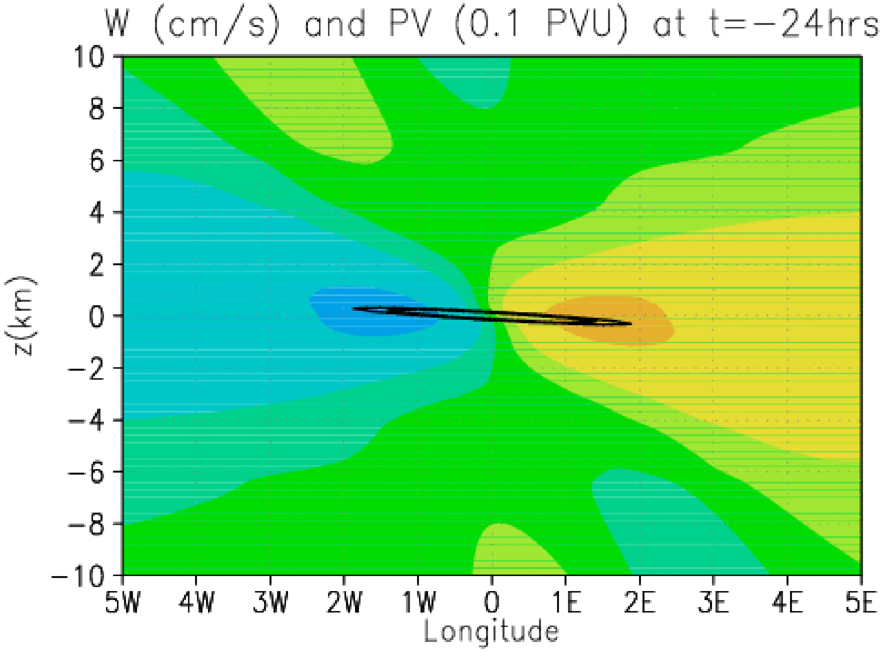

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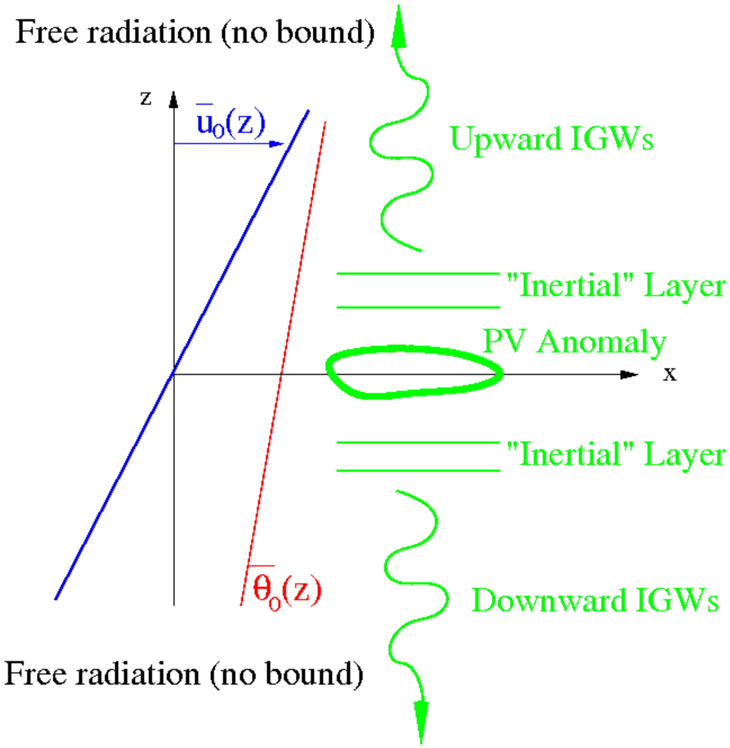

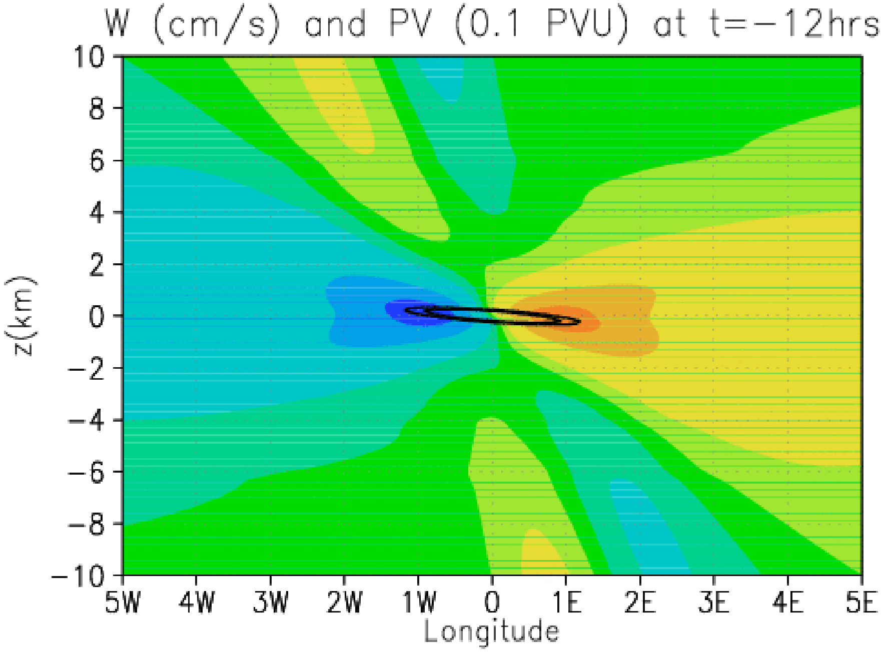

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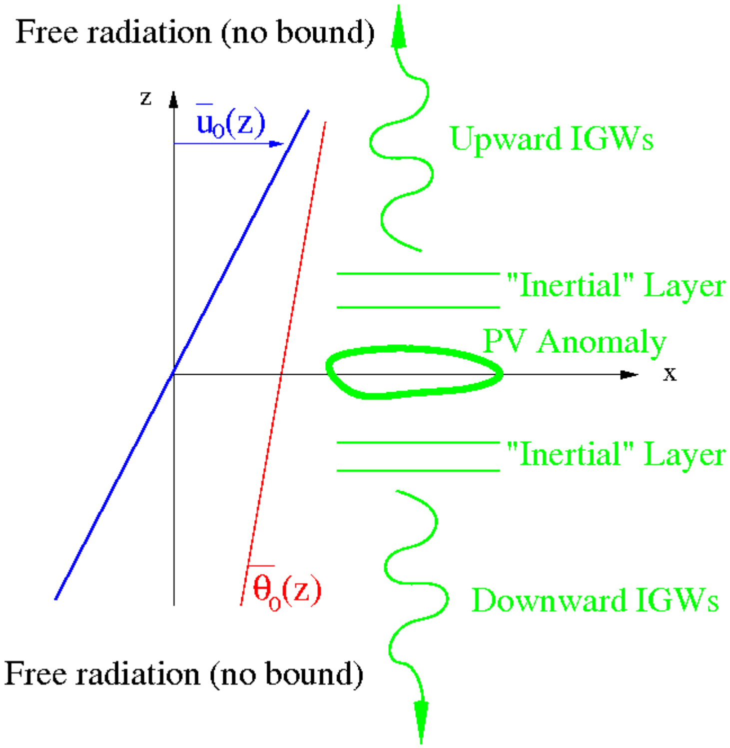

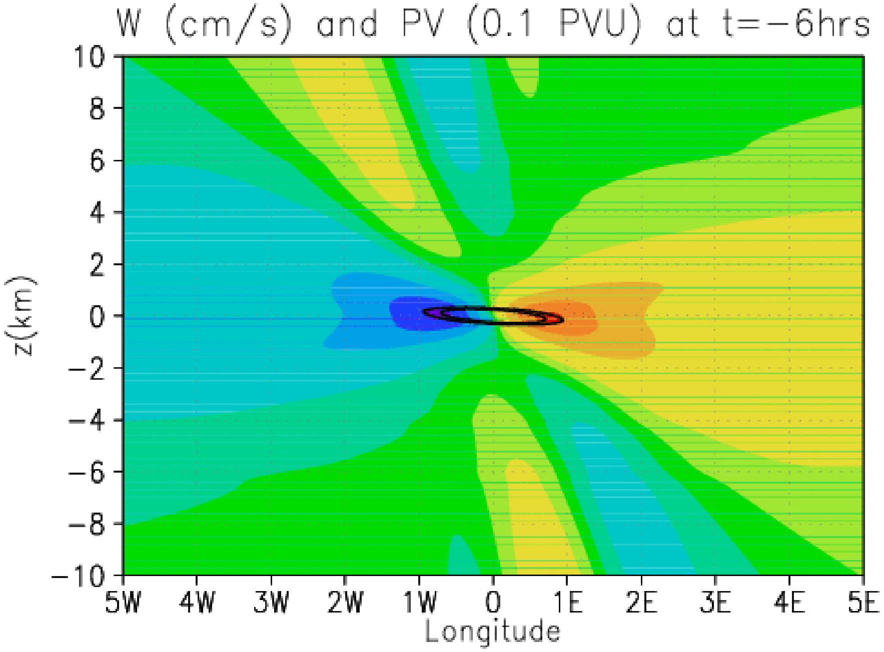

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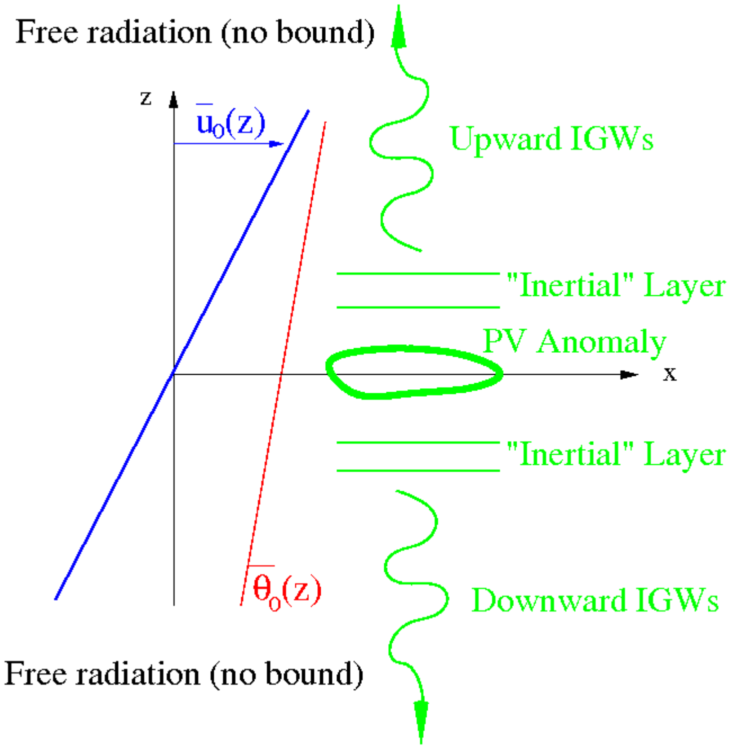

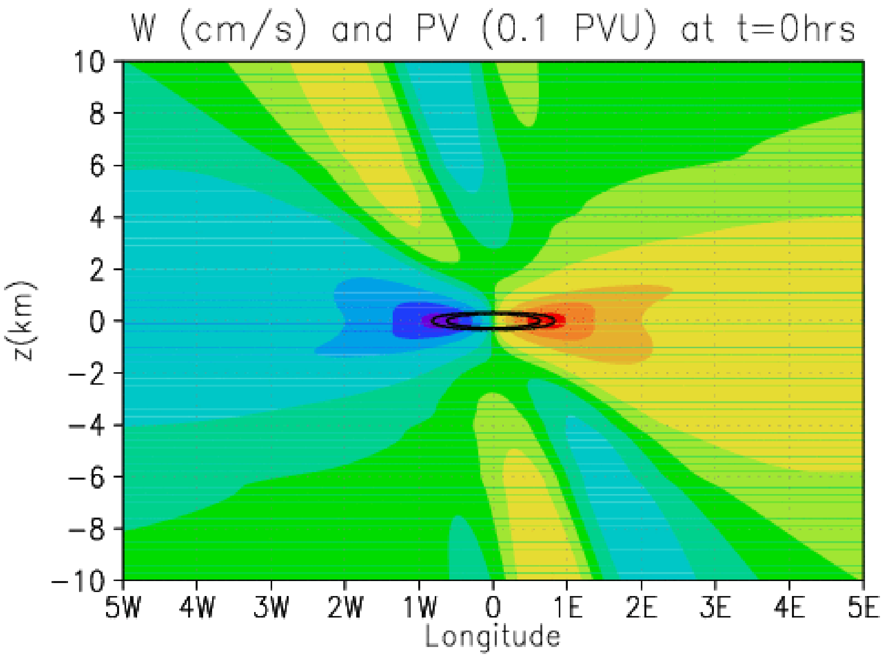

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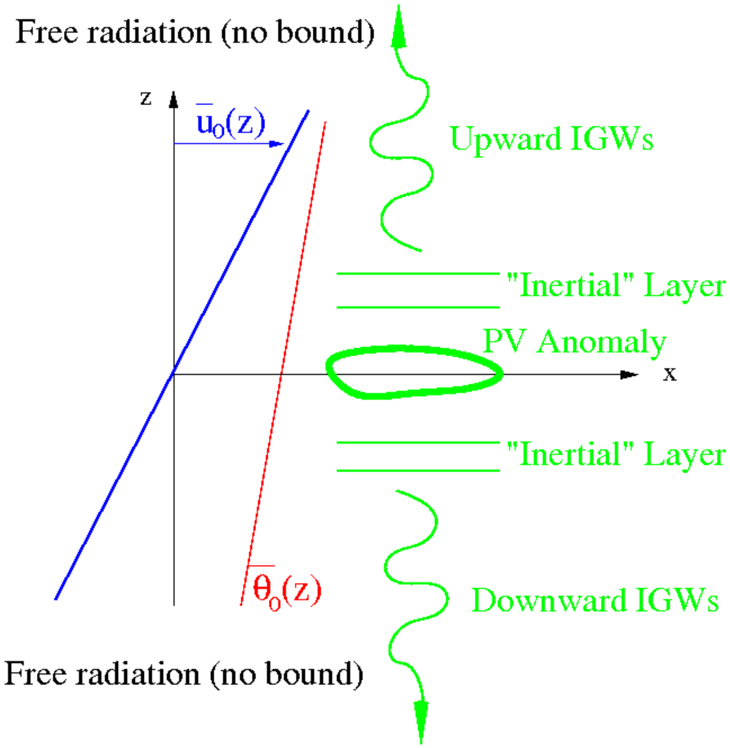

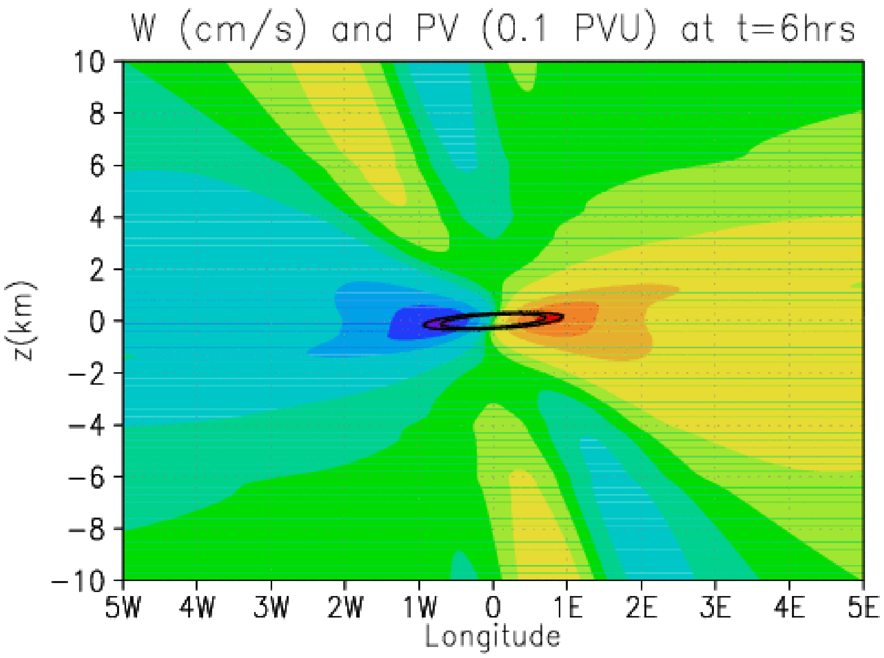

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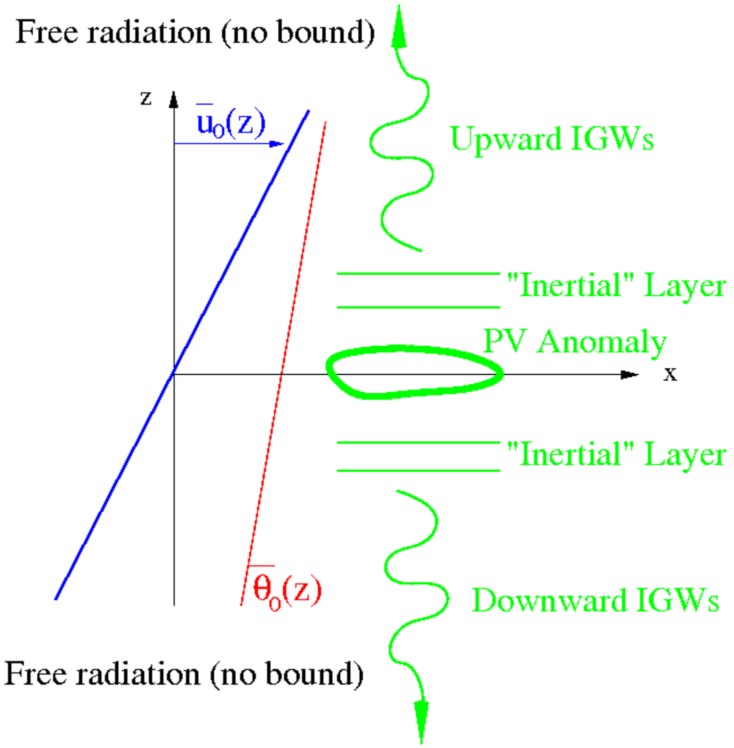

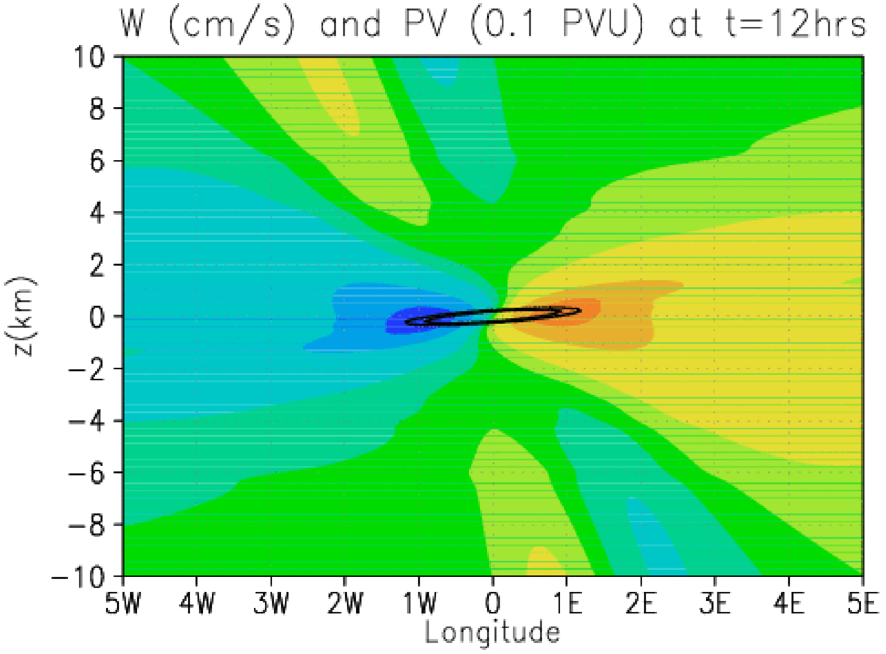

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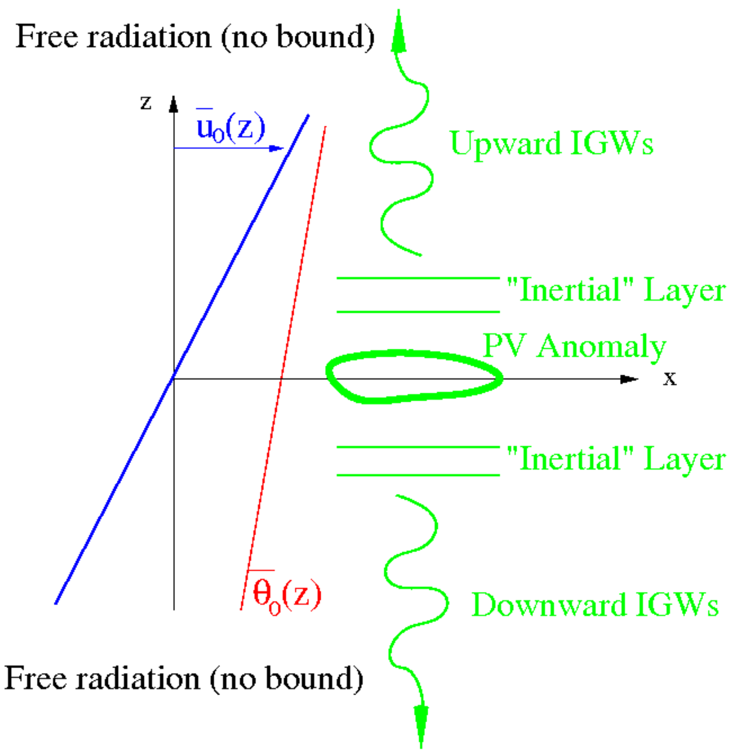

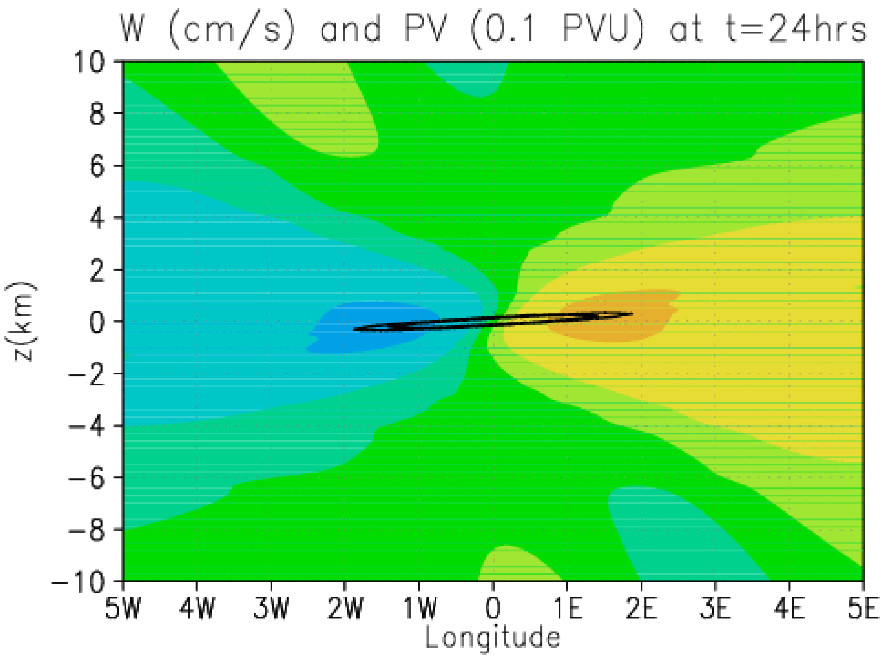

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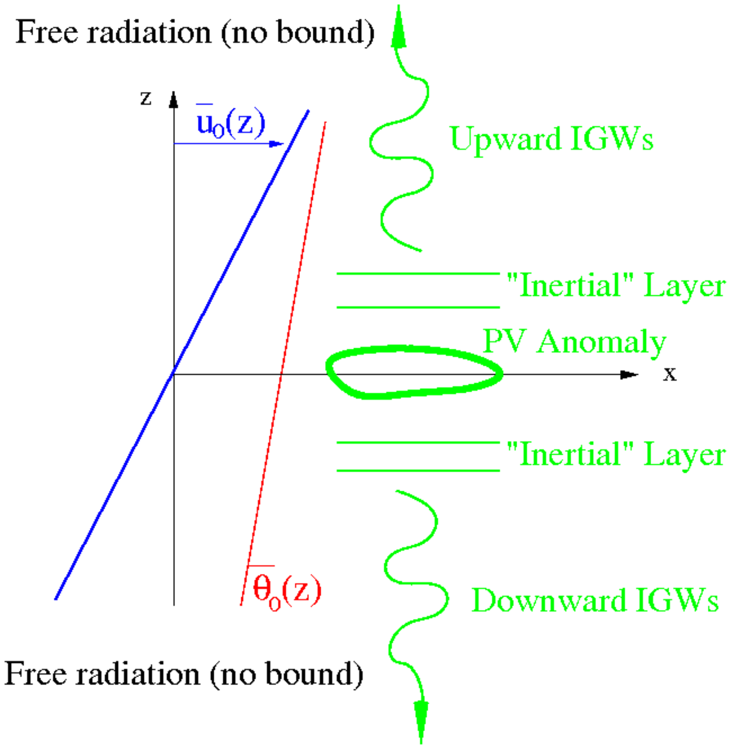

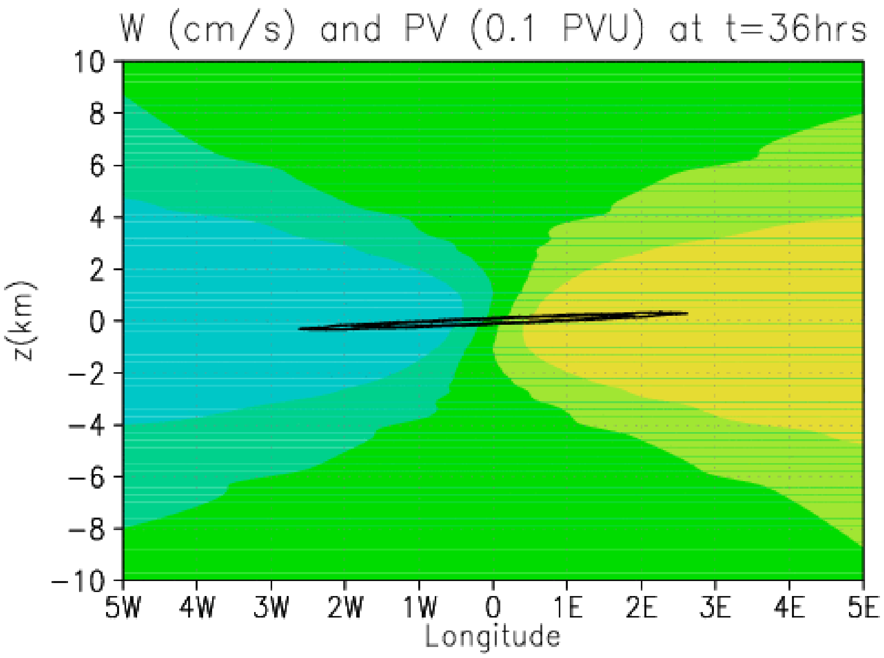

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Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

The canonical solution $W(\xi)$ corresponds to a $\delta(\xi)$-PV distribution:

$$-W_{\xi\xi} + \left(\frac{W_\xi}{\xi^2}\right)_\xi + \left(\frac{2i\nu W}{\xi^2}\right)_\xi - \frac{J(1+\nu^2)}{\xi^2} W = \delta(\xi)$$

$\xi >> 1$: $E\,\xi^{1/2+i\mu}$ (upward GW)

$\xi > 1$: $E\,(1+\xi)^{-i\nu}\xi^{1/2+i\nu+i\mu}F(1-\xi^{-2})$

In $\xi=1$ the CL continuation links E with A and B

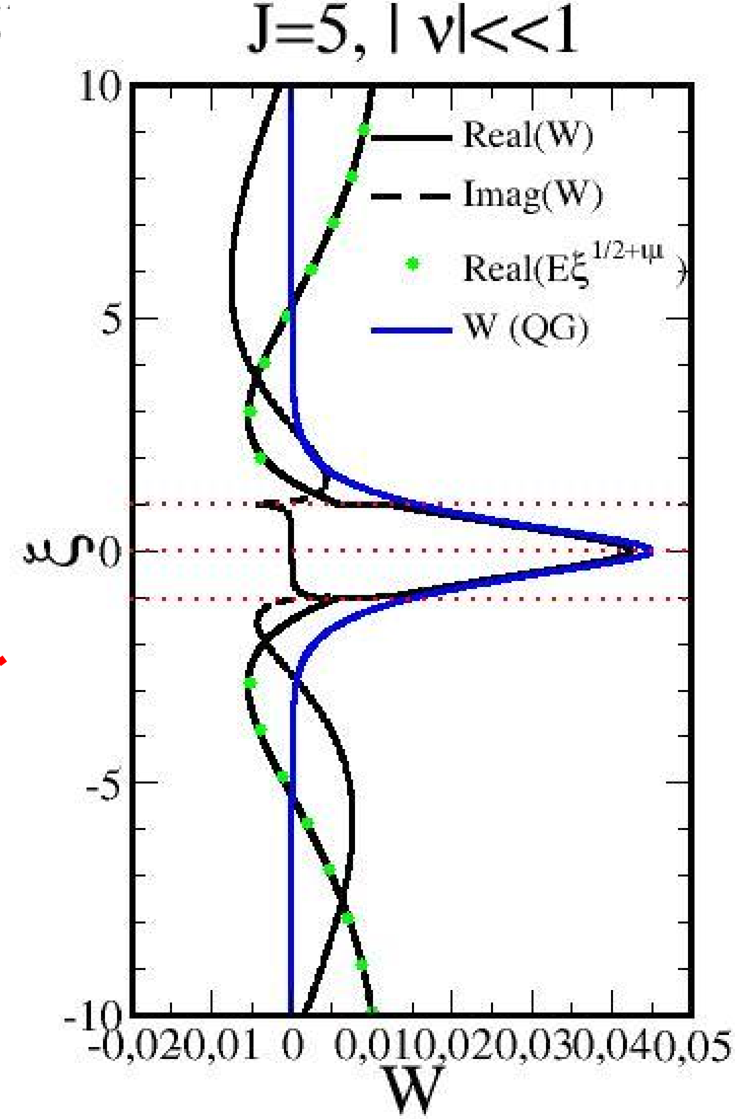
$0<\xi<1$: $(1+\xi)^{-i\nu}(A\,F'(\xi^2)+B\xi^3F''(\xi^2))$

B and A such that $W_\xi/\xi^2(0^+)-W_\xi/\xi^2(0^-)=1$

$-1<\xi<0$: $(1-\xi)^{+i\nu}(A^*\,F'^*(\xi^2)-B^*\xi^3F''^*(\xi^2))$

$\xi<<-1$: $E^*|\xi|^{1/2-i\mu}$ (downward GW)

F, *F′*, and *F''* Hypergeometric functions



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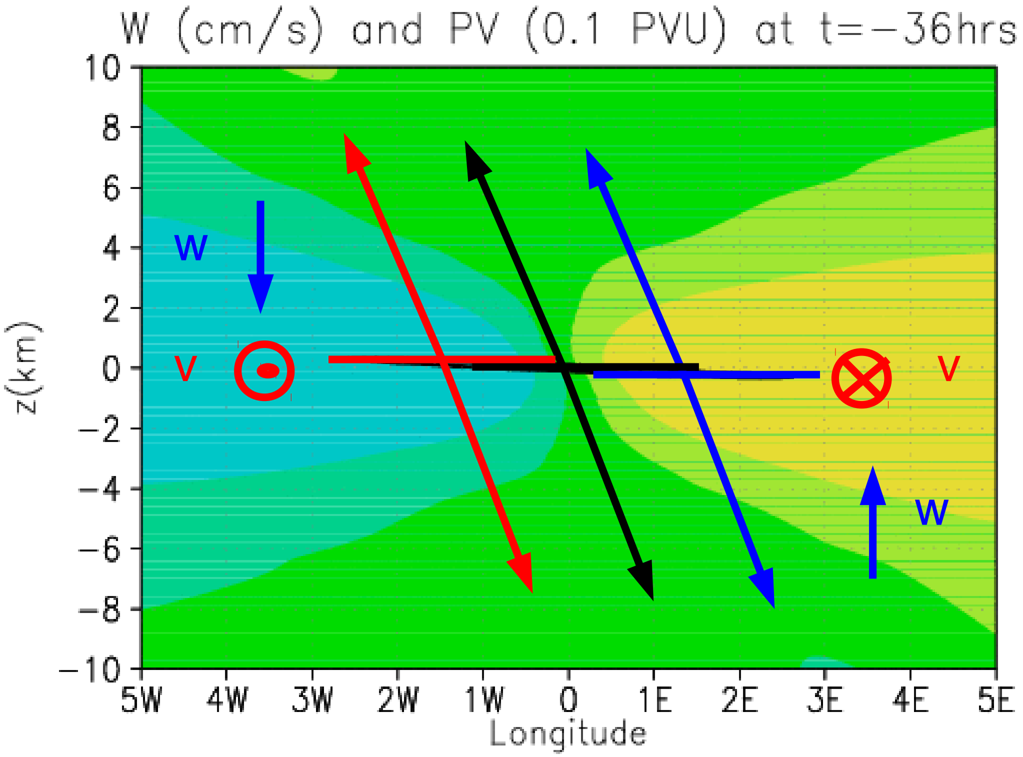
$wN^2 \sim f\Lambda v$



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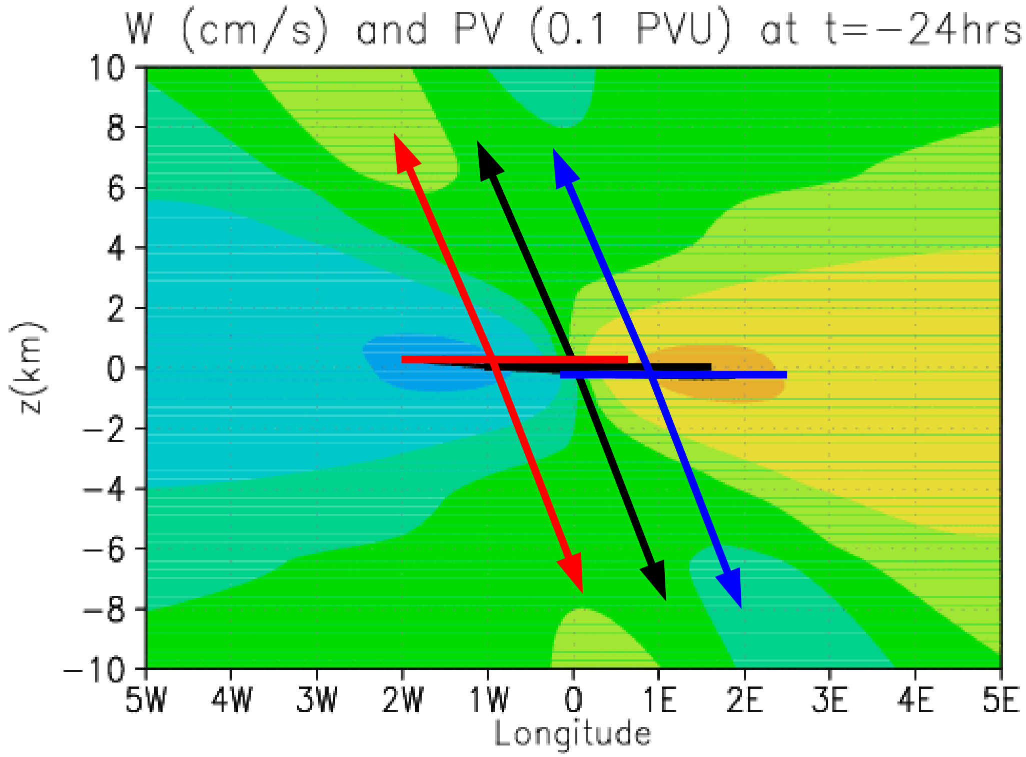

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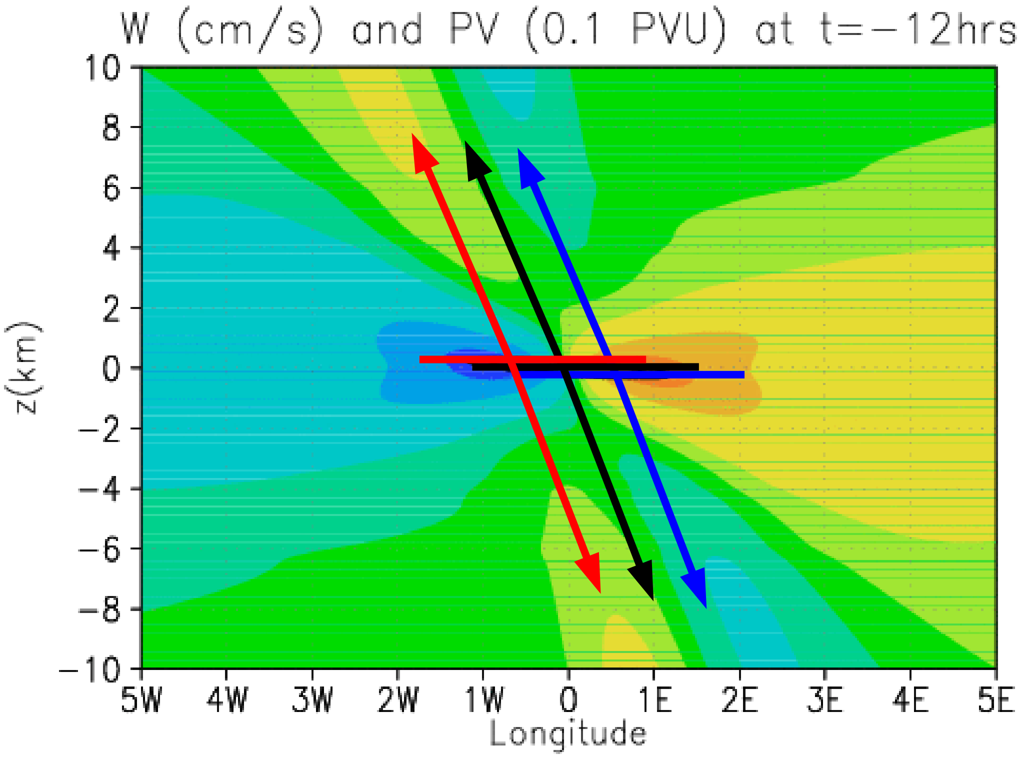

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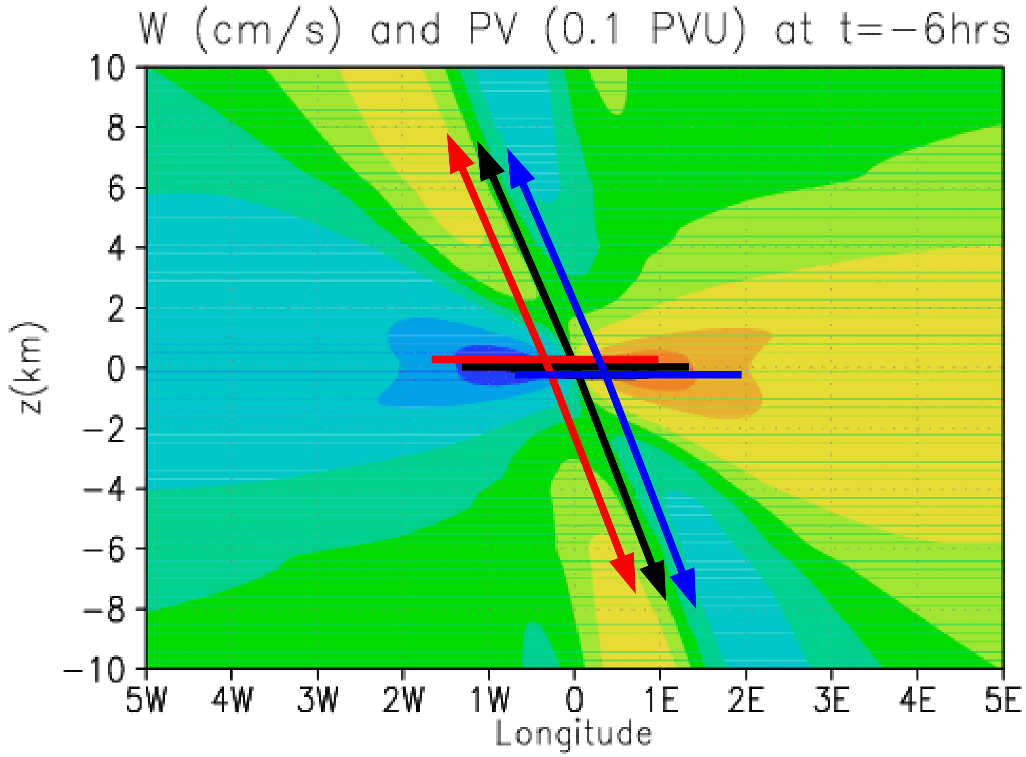

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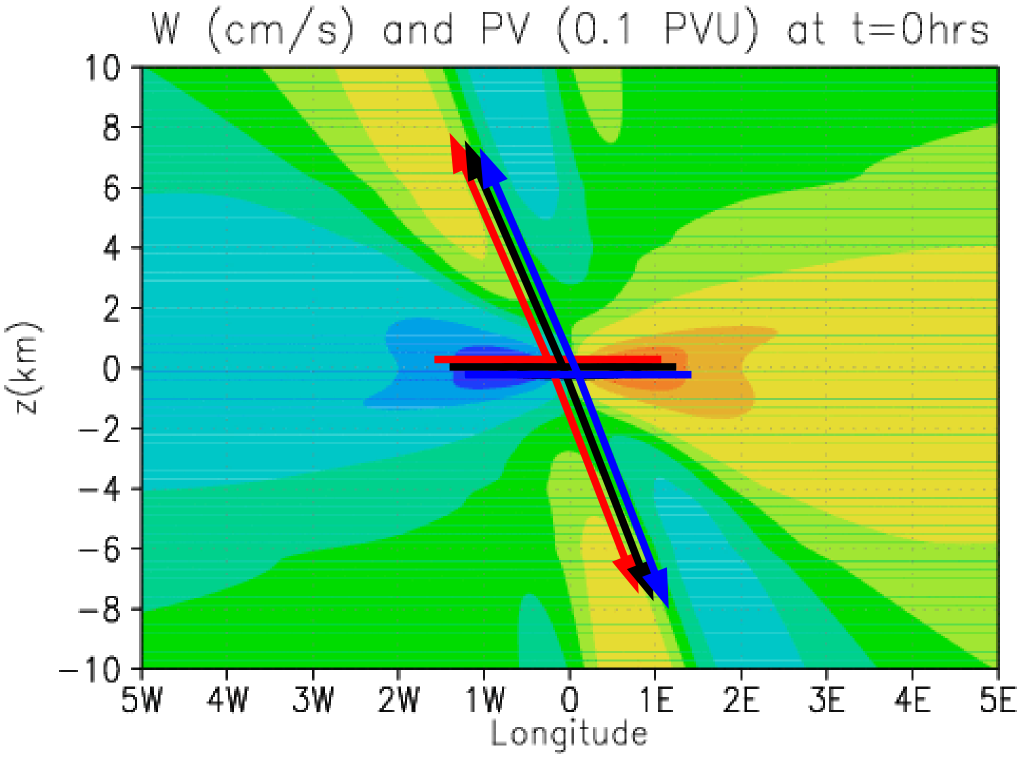

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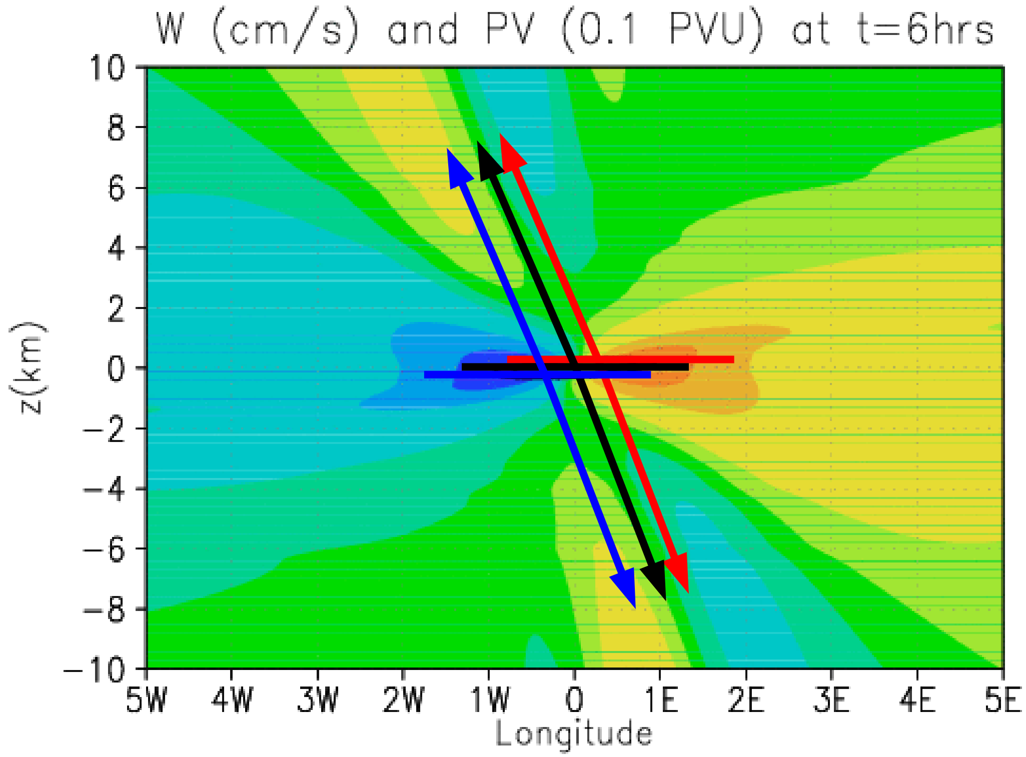
<u>General setup:</u> A 3D (x,y,z) PV anomaly advected in a rotating (*f*=cte), stratified (BV freq *N*=cte) shear flow (vertical shear Λ=cte).



Lott, Plougonven and Vanneste, JAS 2010, 2012.

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

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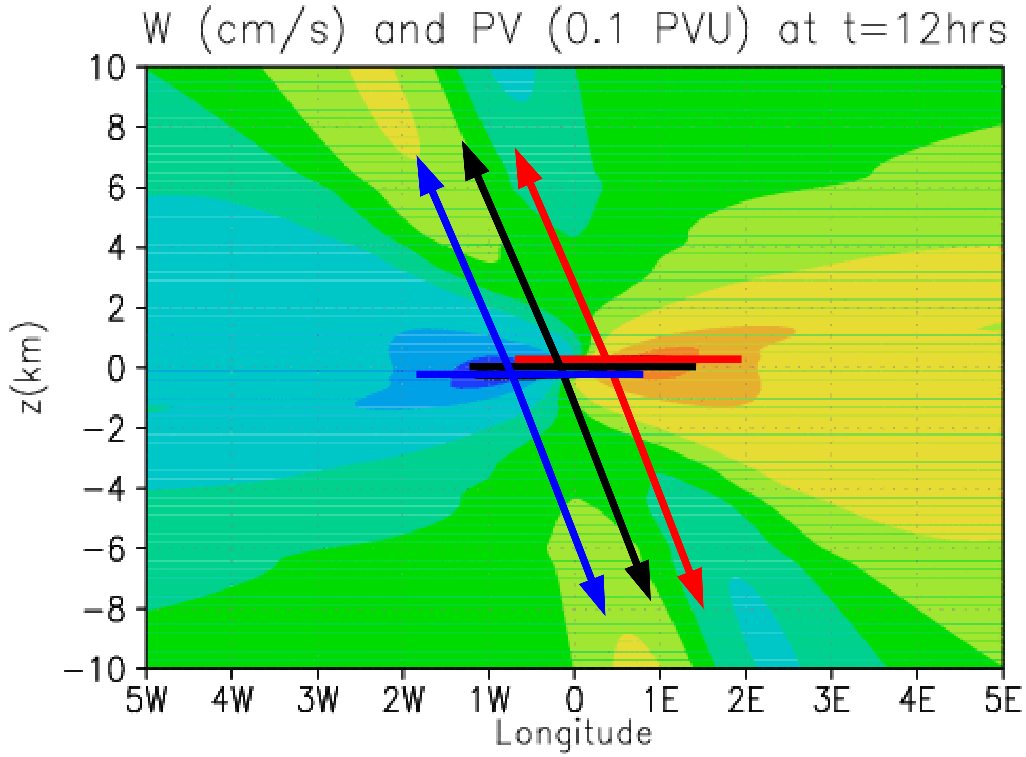

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Parameterization of GWs in large scale models
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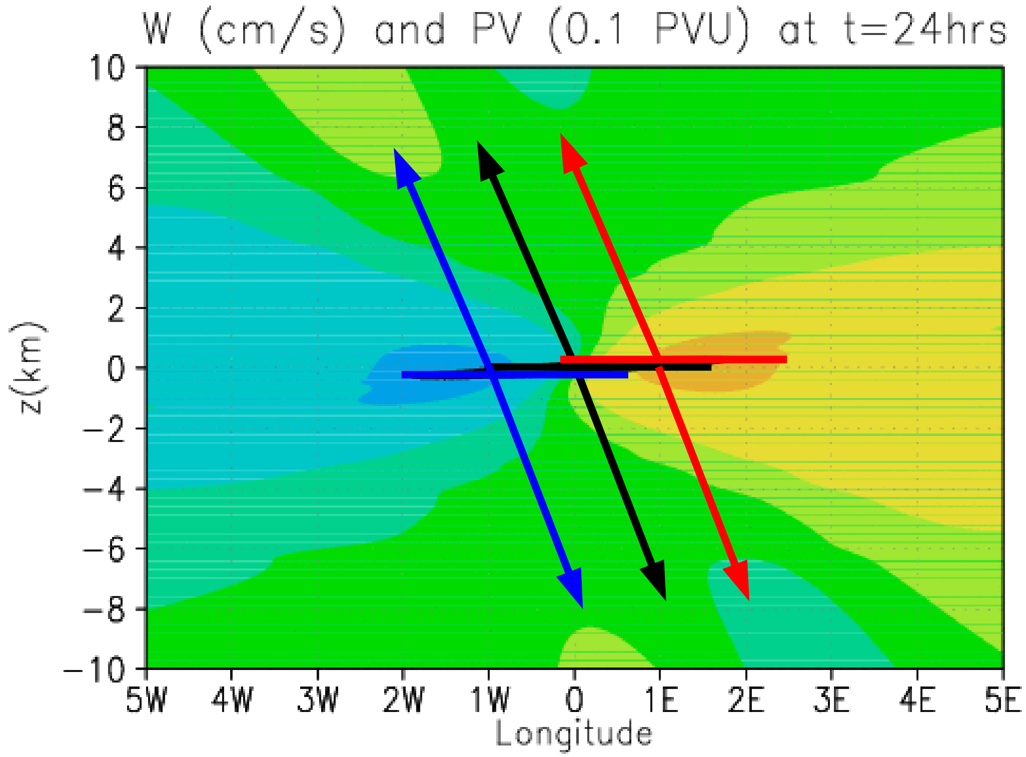

Lott, Plougonven and Vanneste, JAS 2010, 2012.

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

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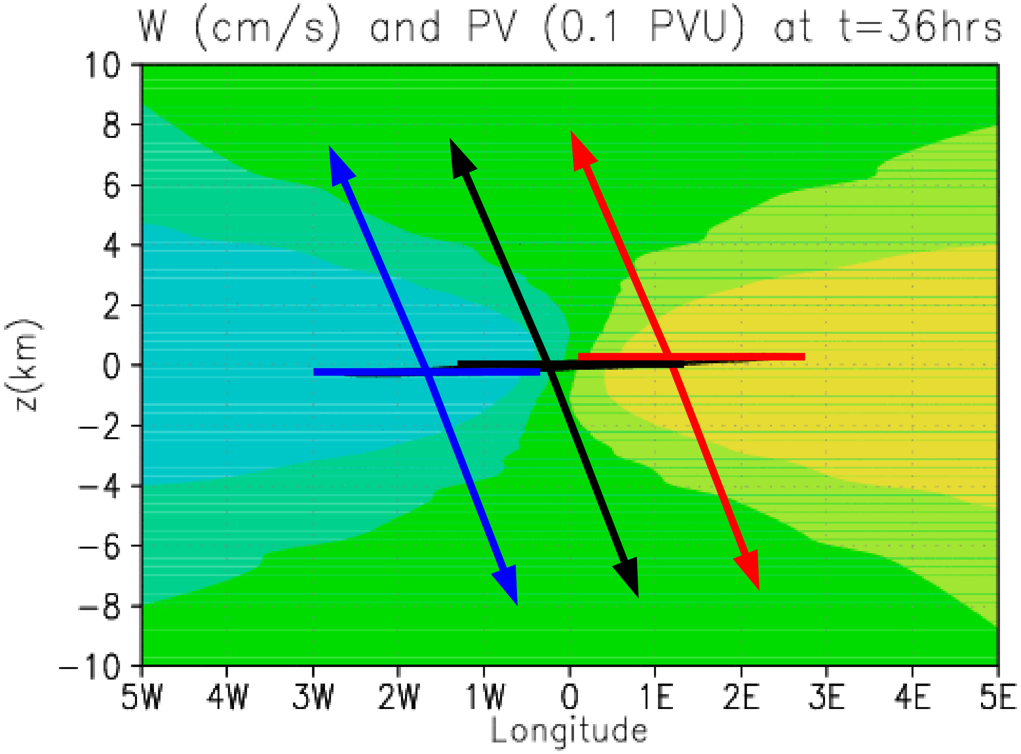


Lott, Plougonven and Vanneste, JAS 2010, 2012.

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

The wave stress is predictable in closed analytical form:

$$F \approx \frac{\rho g^2}{f \theta^2 N^3} \left(\rho q' \sigma_z \right)^2 \frac{e^{-\pi \frac{N}{\Lambda}}}{4}$$

PV anomaly

Characteristic depth
of the PV anomaly

Valid for various PV distributions, and over long time scale (compared to the ½ hour interval at which subgrid-scale parameterisation routinesare updated)

We next take for the PV q the GCM gridscale PV anomalies (as a measure of the subgrid scales one, again a "white" spectrum *hypothesis*)

Including the frontal waves, see next presentation, now it is the subgrid scale vorticity which is considered as a "white" stochastic series:

$q' = \sum_{n=1}^{\infty} C_n q_n'$ where $q_n' = \Re\left[\hat{q}_n e^{i(\vec{k}_n \cdot \vec{x} - \omega_n t)} \right]$ taking $|\hat{q}_n| = |q_r|$

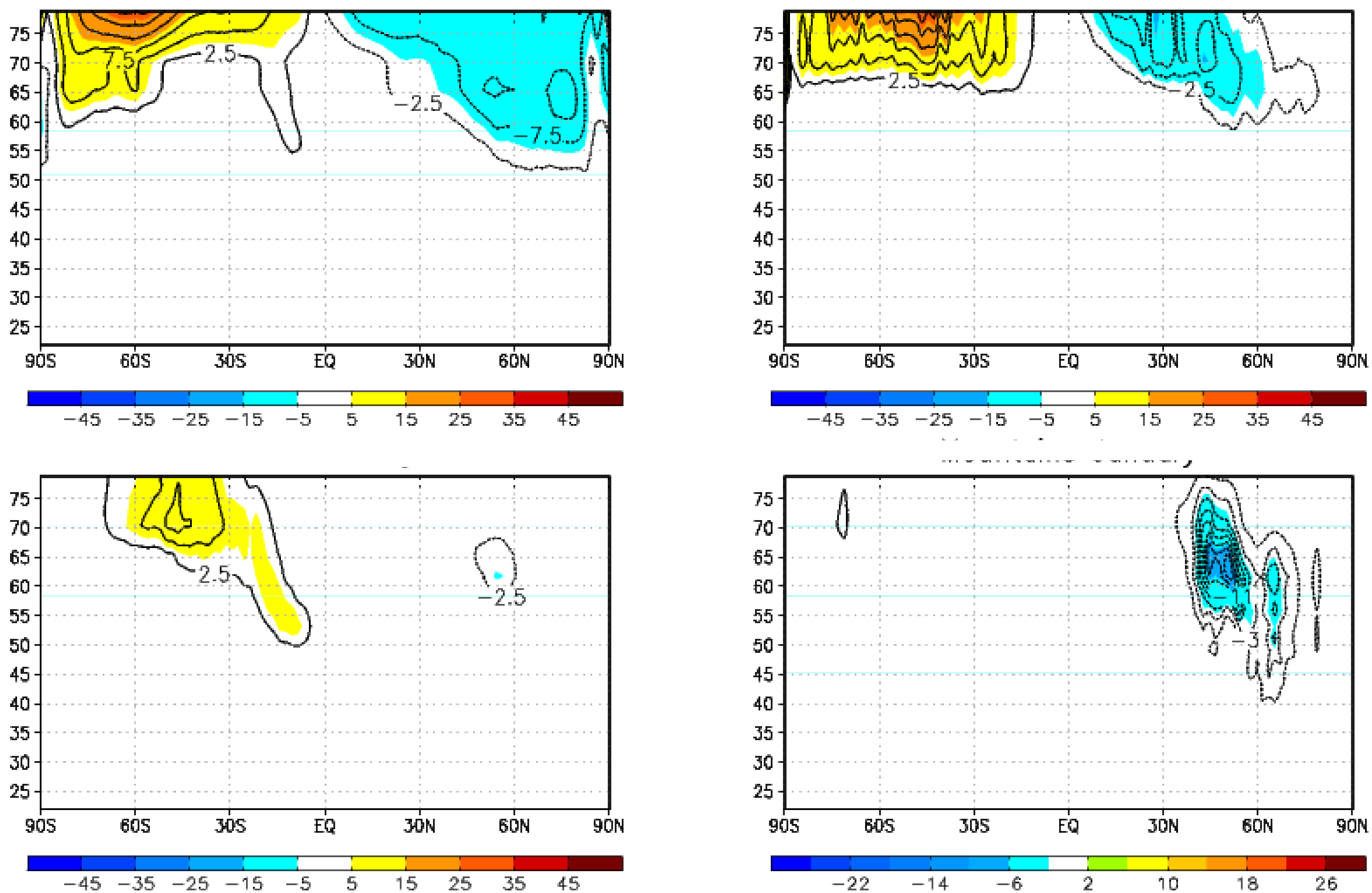
de la Camara and Lott 2015

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

The theory predicts about the right amount of drag compared to a highly tuned globally spectral scheme (January, all in m/s/day)

Globally spectral scheme

From fronts

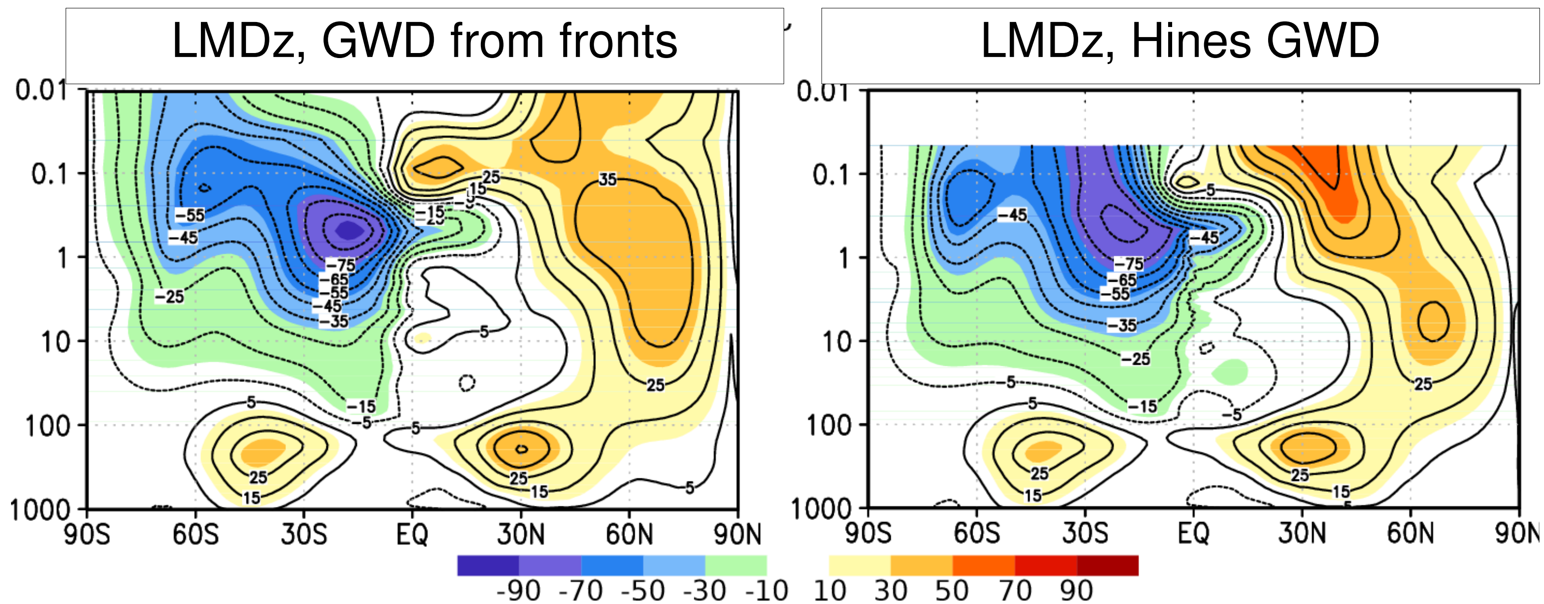


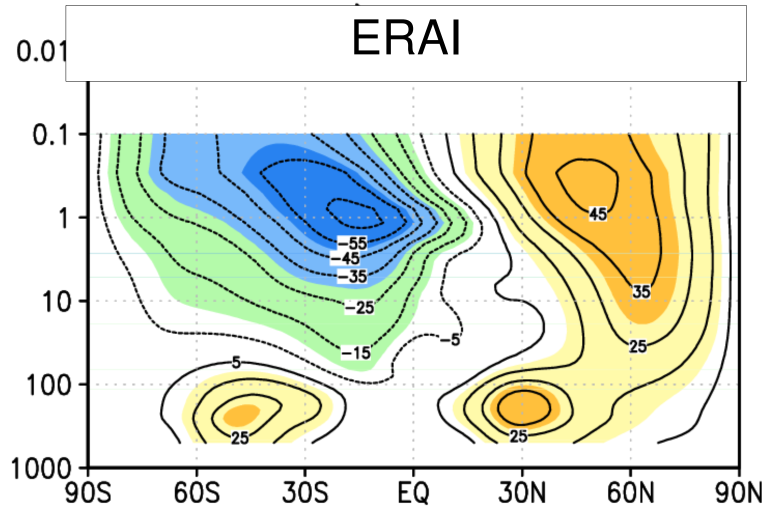
Convective GWs

Mountains GWs

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Zonal wind U, January climatology



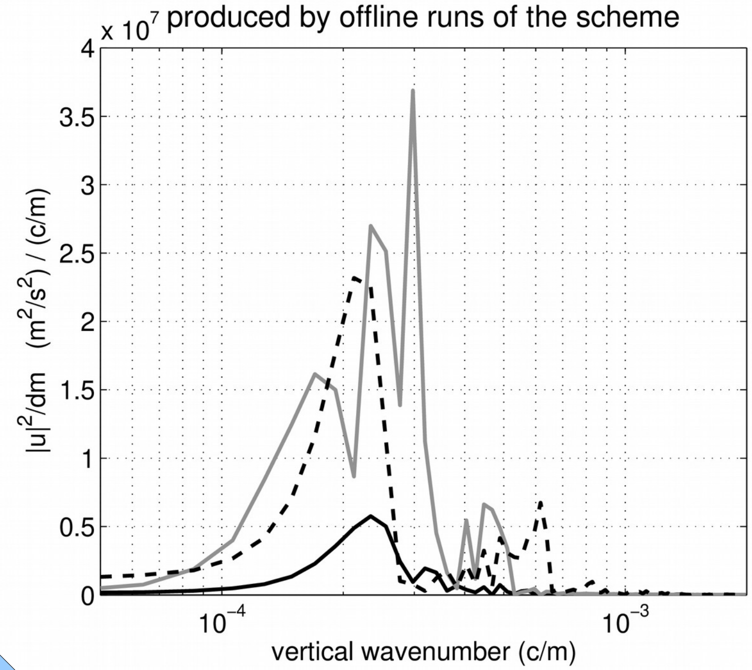


The performance of the scheme
Compares with what was obtained
with the Hines Scheme in
Lott et al. (C. Dyn.2005,)

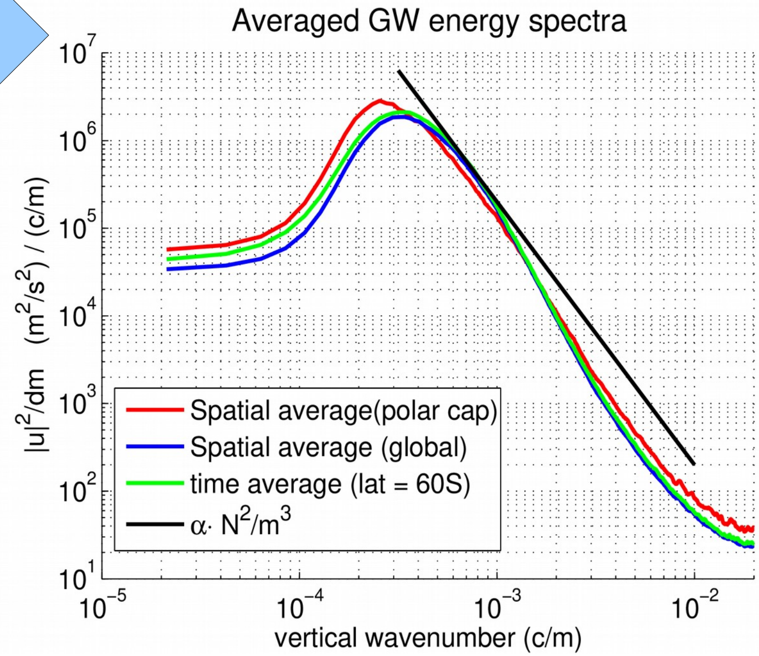
Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Vertical spectra of GWs energy

The observed “universal spectra” can be obtained with a “multiwave scheme” as a superposition of individual periodograms of GW packets.



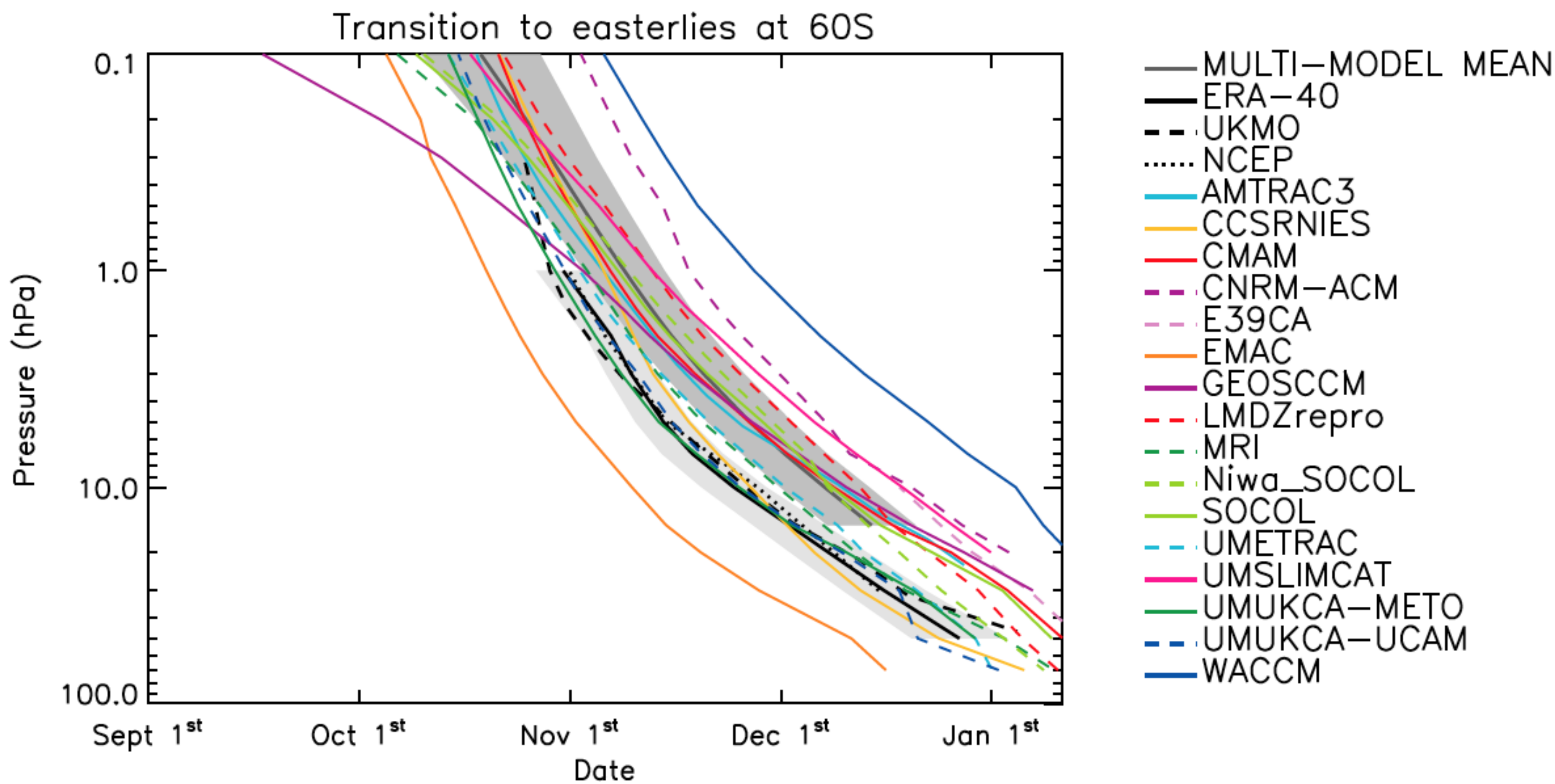
Average of periodograms



de la Cámara et al. 2015

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Butchart et al. 2011, *JGR*, *date when u(60S) fall below 10m/s*



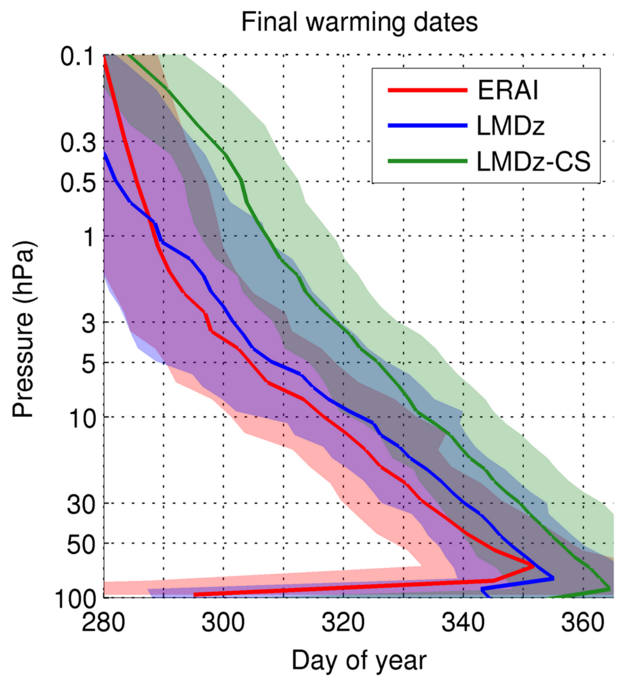
Insufficient parameterized GW drag at 60°S as cause of late final warming bias

(McLandress et al., 2012 *JAS*)

Due to lateral propagation of orographic waves? (Sato et al. 2009)

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Test with constant sources (CS) against source related Gws.
Source related GWs predict an earlier breakdown
(Effect due to intermittency again?)



In the SH, the final warming dates times the winter vortex breakdown:
date when u(60S) fall below 10m/s

de la Camara et al. JAS 2016

Parameterization of GWs in large scale models
5) Validation against balloon observations

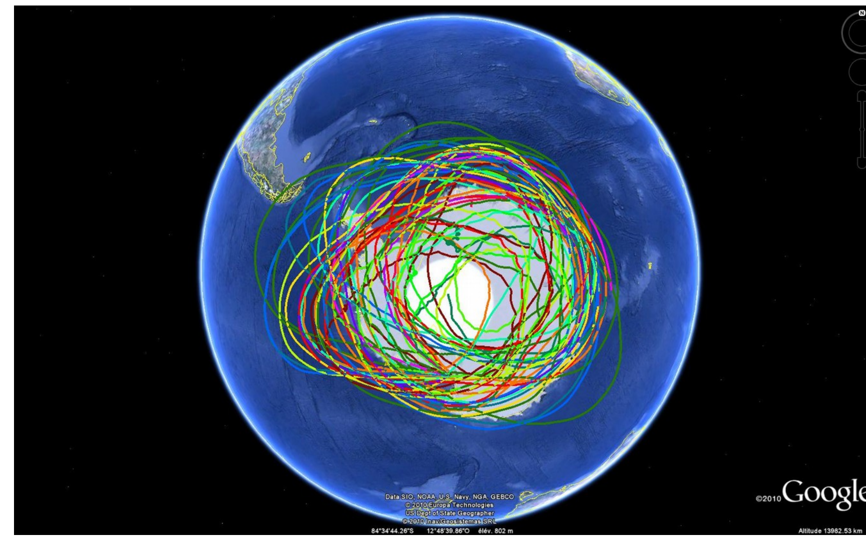
Mid latitudes and Concordiasi

GWs from the scheme:

Offline runs using ERAI and GPCP data corresponding to the Concordiasi period.

Important: Satellite (partial) observations in the tropics support what is shown next.

www.lmd.polytechnique.fr/VORCORE/Djournal2/Journal.htm



CONCORDIASI (2010)

Rabier et al. 2010 BAMS

19 super-pressure balloons launched from McMurdo, Antarctica, during Sep and Oct 2010.

The balloons were at ~ 20 km height.

www.lmd.polytechnique.fr/VORCORE/Djournal2/Journal.htm

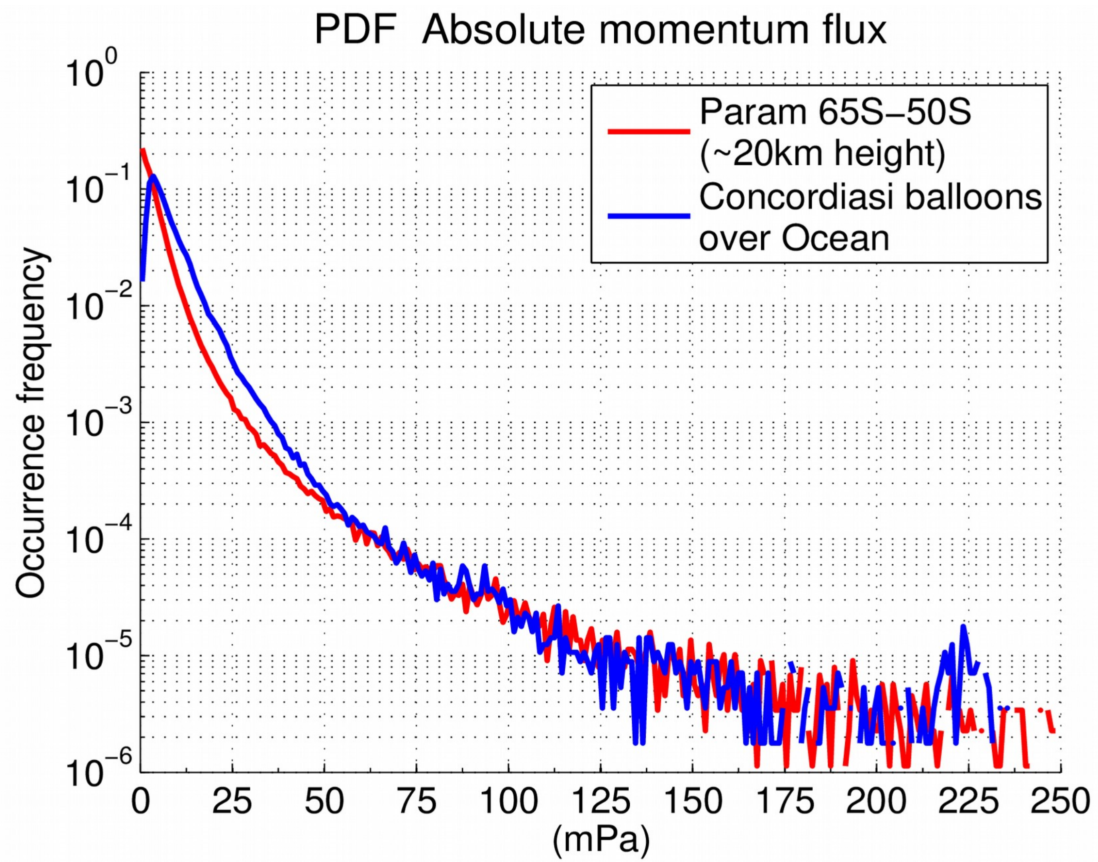
Dataset of GW momentum fluxes *(as by Hertzog et al. 2008)*

Parameterization of GWs in large scale models
5) Validation against balloon observations

Mid latitudes and Concordiasi

Intermittency of GW momentum flux

The stochastic scheme parameters can be tuned to produce fluxes as intermittent as in balloon observations.
An effect in good part due to the inclusion of the sources (convective and frontal)



Intermittency is important because it produces GW breaking at lower altitudes *(Lott&Guez 2013, de la Cámara et al. 2015*

Parameterization of GWs in large scale models
5) Validation against balloon observations

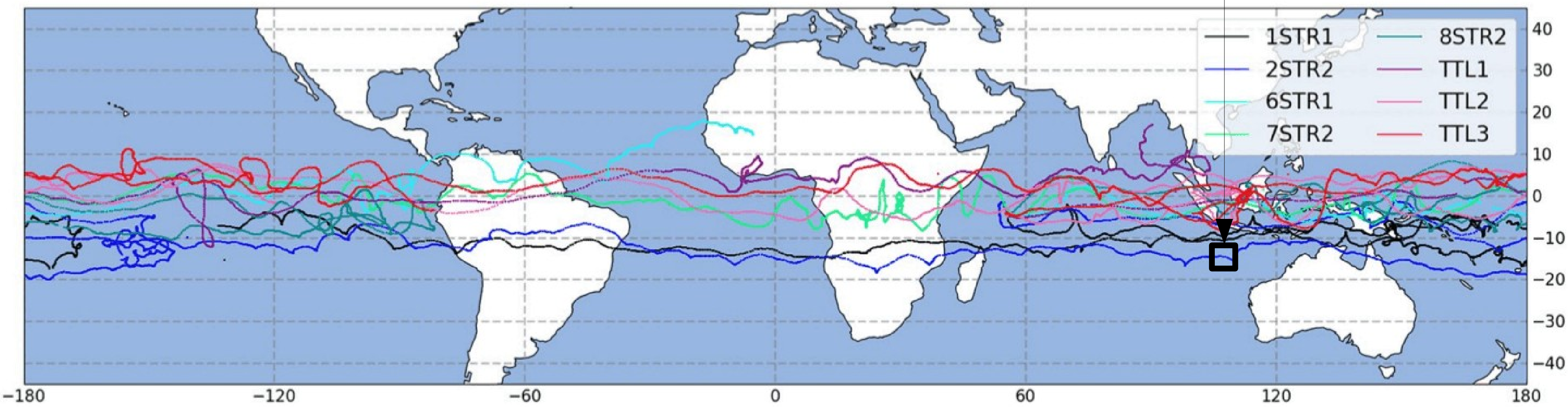
Convective gravity waves and the tropics : Strateole 2

Strateole 2, period 1 (Nov.2019-Feb. 2020, Corcos et al. 2021)

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

5°x5° ERA5 1° data
Centered on balloon



Strateole 2 phase 1, Nov 2019-Feb . 2020
8 Balloon 2- to 3 months flights at about z=20km

. Ma

Adapted from Corcos et al. JGR2021

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

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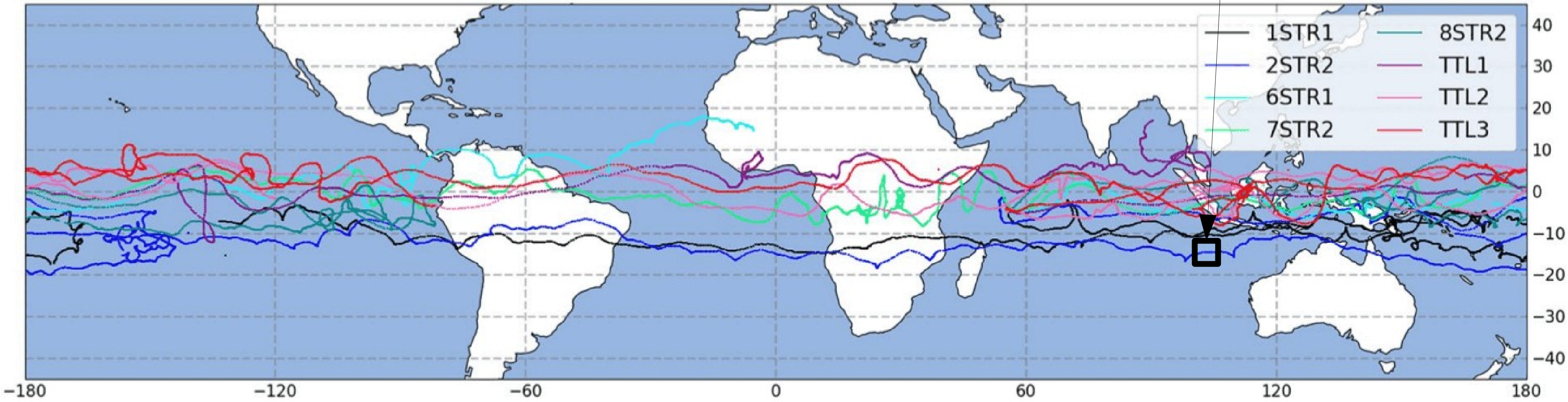

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5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

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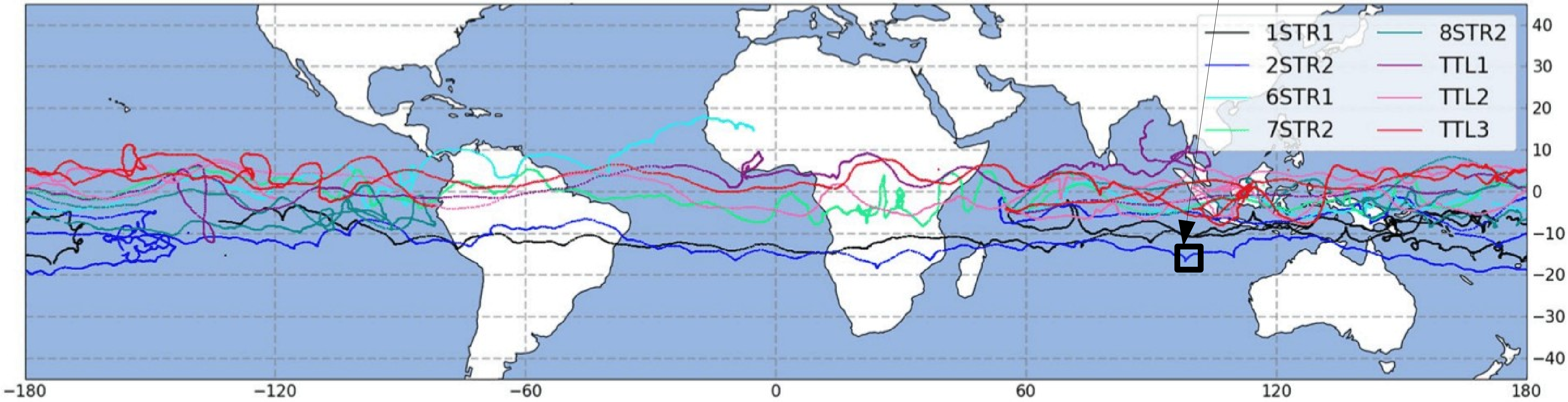

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Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

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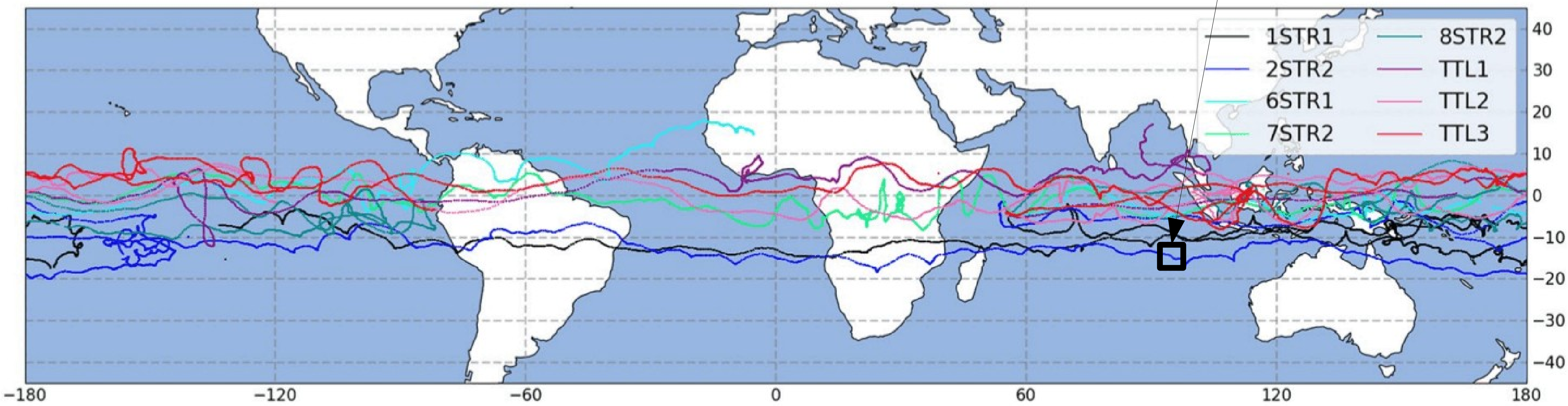

Ma

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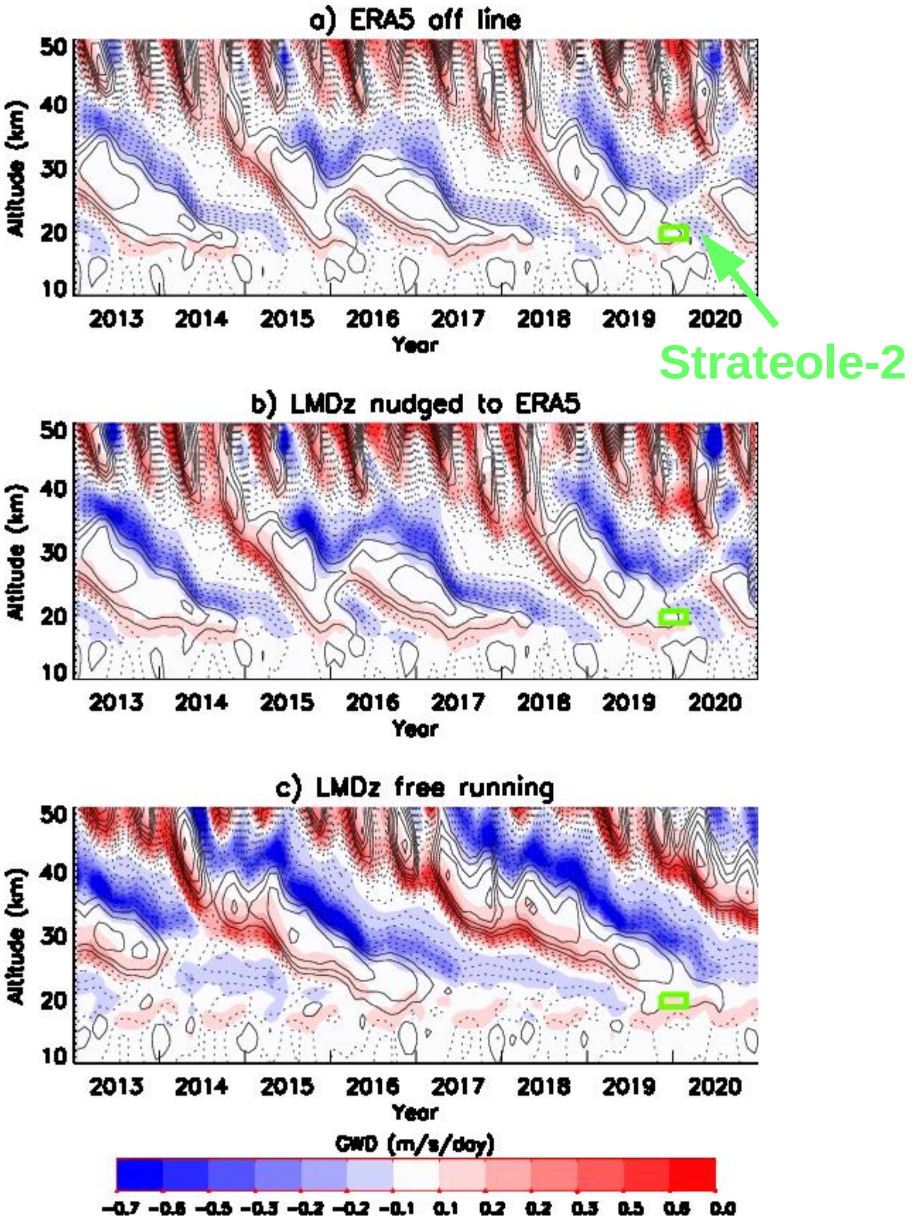
Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Online-offline and nudge results with LMDz, large scale Fields from ERA5

GWD tendencies from Lott et al. (2013), adapted to IPSLCM6 Hourdin et al. (2020)



Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

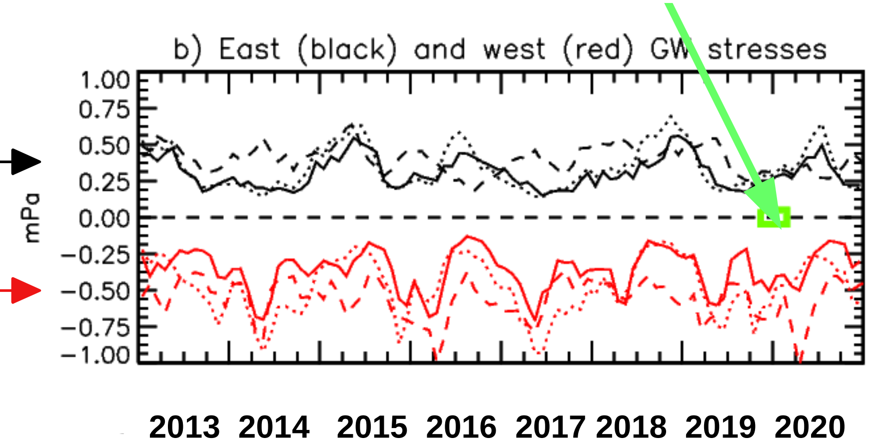
Online-offline and nudge results with LMDz, large scale Fields from ERA5

East and west stress at z=20km

Strateole-2

+0.4mPa

-0.5mPa

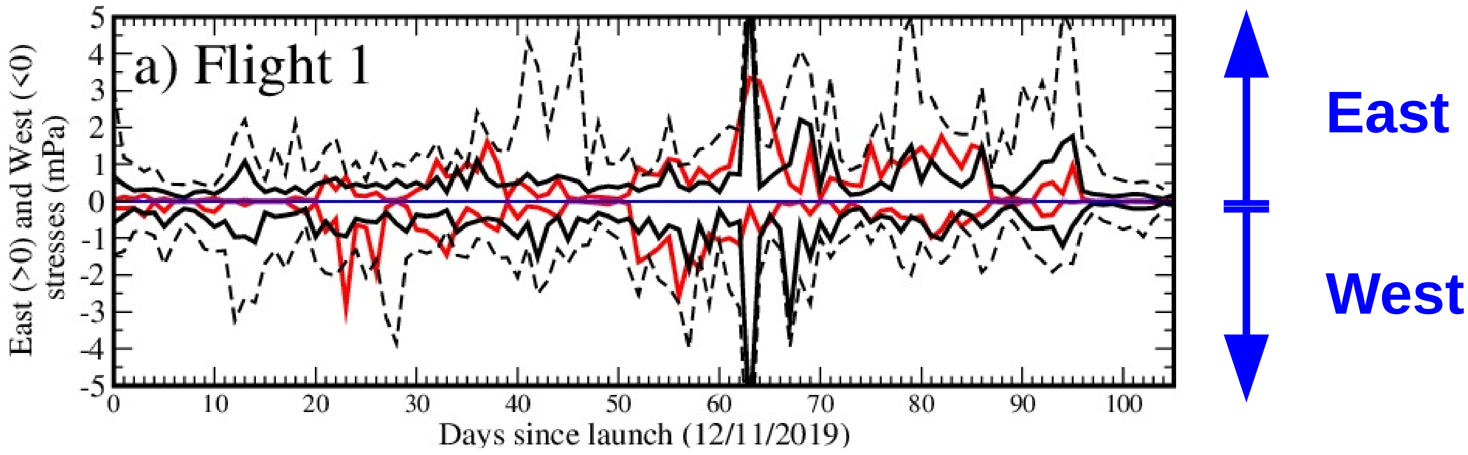


Zonally Averaged fluxes at about z=20 km have values around 0.4-0.5mPa

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

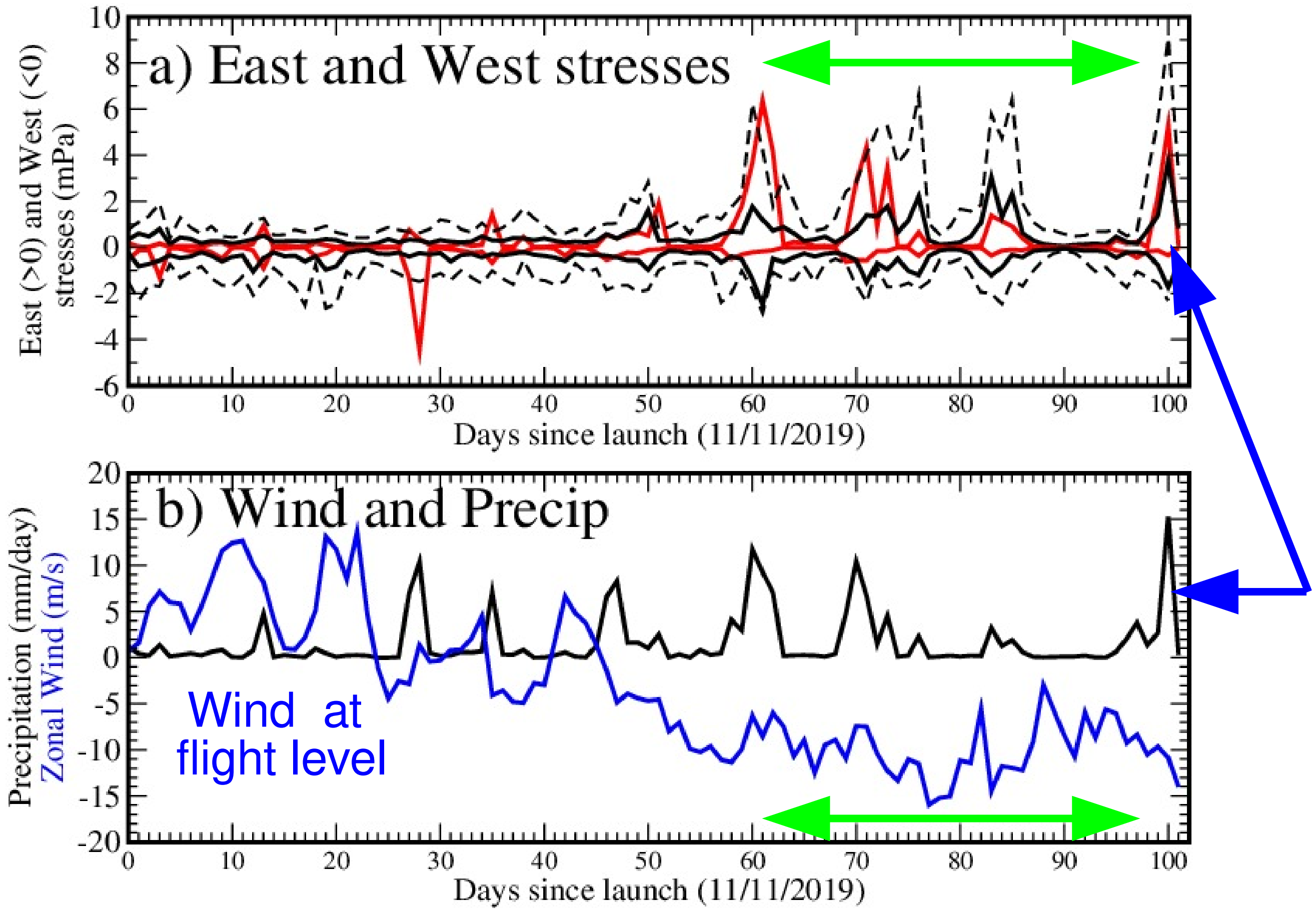
Good correspondance between observation and prediction (15mn-1hr waves)



Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Evidence of dynamical filtering and relation with precipitation, case of Flight 2



More Eastward flux when Wind is westward

More flux when precipiation peaks

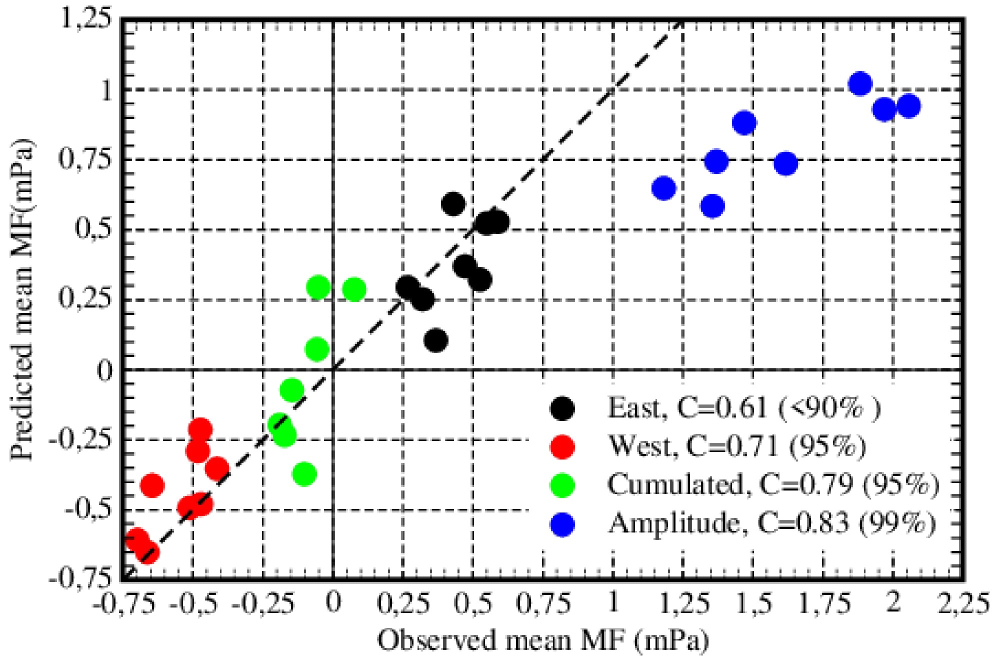
Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

East and West MF averaged over the entire (8) balloon flights
Offline predictions as function of observed momentum fluxes
(15mn-1hr)

+0.4mPa

-0.5mPa



We scientists are not fools !

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Correlation values daily data (“intraflight”),
flight by flight

Flight	Altitude	Launch	End	Duration/DOF	Cumulated	Amplitude	East	West
01_STR1	20.7	12/11/2019	28/02/2020	107/53	0.23	**0.28**	**0.46**	*0.07*
02_STR2	20.2	11/11/2019	23/02/2020	103/51	*0.21*	**0.62**	**0.62**	*0.05*
03_TTL3	19.0	18/11/2019	28/02/2020	101/33	**0.49**	**0.42**	**0.49**	**0.43**
04_TTL1	18.8	27/11/2019	02/02/2020	67/22	**0.41**	**0.55**	**0.55**	**0.53**
05_TTL2	18.9	05/12/2019	23/02/2020	79/19	0.36	*0.29*	0.36	*0.24*
06_STR1	20.5	06/12/2019	01/02/2020	57/10	*0.39*	**0.67**	**0.71**	**0.59**
07_STR2	20.2	06/12/2019	28/02/2020	83/16	*0.01*	*0.09*	*0.08*	*0.06*
08_STR2	20.2	07/12/2019	22/02/2020	77/12	*0.18*	**0.7**	**0.66**	*0.37*
ALL	x	x	x	670/170	**0.30**	**0.41**	**0.51**	**0.29**

1-sided Pearson test according to the DOF and for each flight :

<90, 90-95, **95-99**, **≥99**

QBOi Models

WMI
Hines
Multiwave

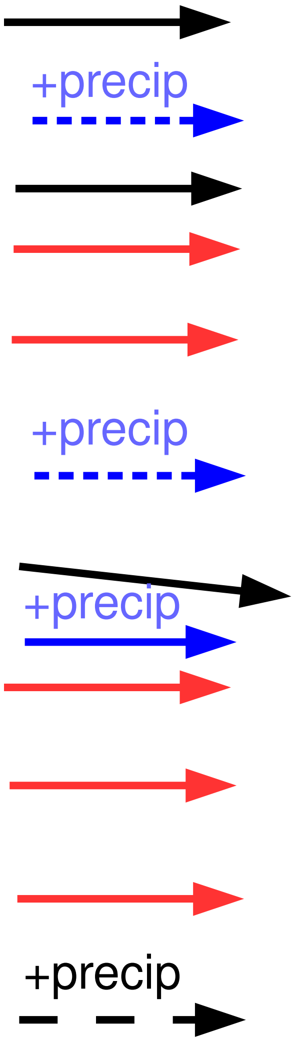


Table 5. Participating models and contact information

Model names	Expts.	Institutes	Investigators	Email address	References
60LCAM5	1-4	NCAR	J. Chen	cchen@ucar.edu	Richter et al. (2014)
			J. Richter	jrichter@ucar.edu	
AGCM3-CMAM	1-3, 5	CCCMa	J. Anstey	james.anstey@canada.ca	Scinocca et al. (2008)
			J. Scinocca	john.scinocca@canada.ca	Anstey et al. (2016)
		U. Toronto	C. McLandress	charles@atmosp.physics.utoronto.ca	
CESM1-	1-4	NCAR	R. Garcia	rgarcia@ucar.edu	
(WACCM-L110)			J. Richter	jrichter@ucar.edu	Garcia and Richter (2017)
EC-EARTH3.1	5	BSC	J. Garcia-Serrano	javier.garcia@bsc.es	Christiansen et al. (2016)
ECHAM5sh	1-4	ISAC-CNR	F. Serva	federico.serva@artov.isac.cnr.it	Serva et al. (2017)
			C. Cagnazzo	c.cagnazzo@isac.cnr.it	Manzini et al. (2012)
EMAC	1-4	KIT	P. Braesicke	peter.braesicke@kit.edu	Jöckel et al. (2005)
			T. Kerzenmacher	tobias.kerzenmacher@kit.edu	Jöckel et al. (2010)
			S. Versick	stefan.versick@kit.edu	
HadGEM2-A	1	Ewha W. U.	Y.-H. Kim	young-ha.kim@ewha.ac.kr	Martin et al. (2011)
		Yonsei U.	H.-Y. Chun	chunhy@yonsei.ac.kr	
HadGEM2-AC	1	Ewha W. U.	Y.-H. Kim	young-ha.kim@ewha.ac.kr	Martin et al. (2011)
		Yonsei U.	H.-Y. Chun	chunhy@yonsei.ac.kr	Kim and Chun (2015b)
IFS43r1	1-5	ECMWF	T. Stockdale	tim.stockdale@ecmwf.int	ECMWF (2016); Orr et al. (2010)
LMDz6	1-4	ISPL-LMD	F. Lott	flott@lmd.ens.fr	Lott et al. (2005, 2012)
MIROC-AGCM-LL	1-5	MIROC	Y. Kawatani	yoskawatani@jamstec.go.jp	Kawatani et al. (2011)
MIROC-ESM	1-5	MIROC	S. Watanabe	wnabe@jamstec.go.jp	Watanabe et al. (2011)
MPI-ESM-MR	5A	MPI	H. Pohlmann	holger.pohlmann@mpimet.mpg.de	Pohlmann et al. (2013)
		U. Hamburg	M. Dobrynin	mikhail.dobrynin@uni-hamburg.de	Dobrynin et al. (2016)
MRI-ESM2	1-5	MRI-JMA	K. Yoshida	kyoshida@mri-jma.go.jp	Adachi et al. (2013)
			H. Naoe	hnaoe@mri-jma.go.jp	Yukimoto et al. (2012)
			S. Yukimoto	yukimoto@mri-jma.go.jp	
UMGA7	1-4	Met Office	A. Bushell	andrew.bushell@metoffice.gov.uk	Walters et al. (2017)
		MOHC	N. Butchart	neal.butchart@metoffice.gov.uk	
		U. Oxford	S. Osprey	scott.osprey@physics.ox.ac.uk	
UMGA7gws	1-4	Met Office	A. Bushell	andrew.bushell@metoffice.gov.uk	Bushell et al. (2015)
		MOHC	N. Butchart	neal.butchart@metoffice.gov.uk	Walters et al. (2017)
		U. Oxford	S. Osprey	scott.osprey@physics.ox.ac.uk	
UMGC2	5A	MOHC	A. Scaife	adam.scaife@metoffice.gov.uk	Dunstone et al. (2016)

Parameterization of GWs in large scale models
5) Validation against balloon observations

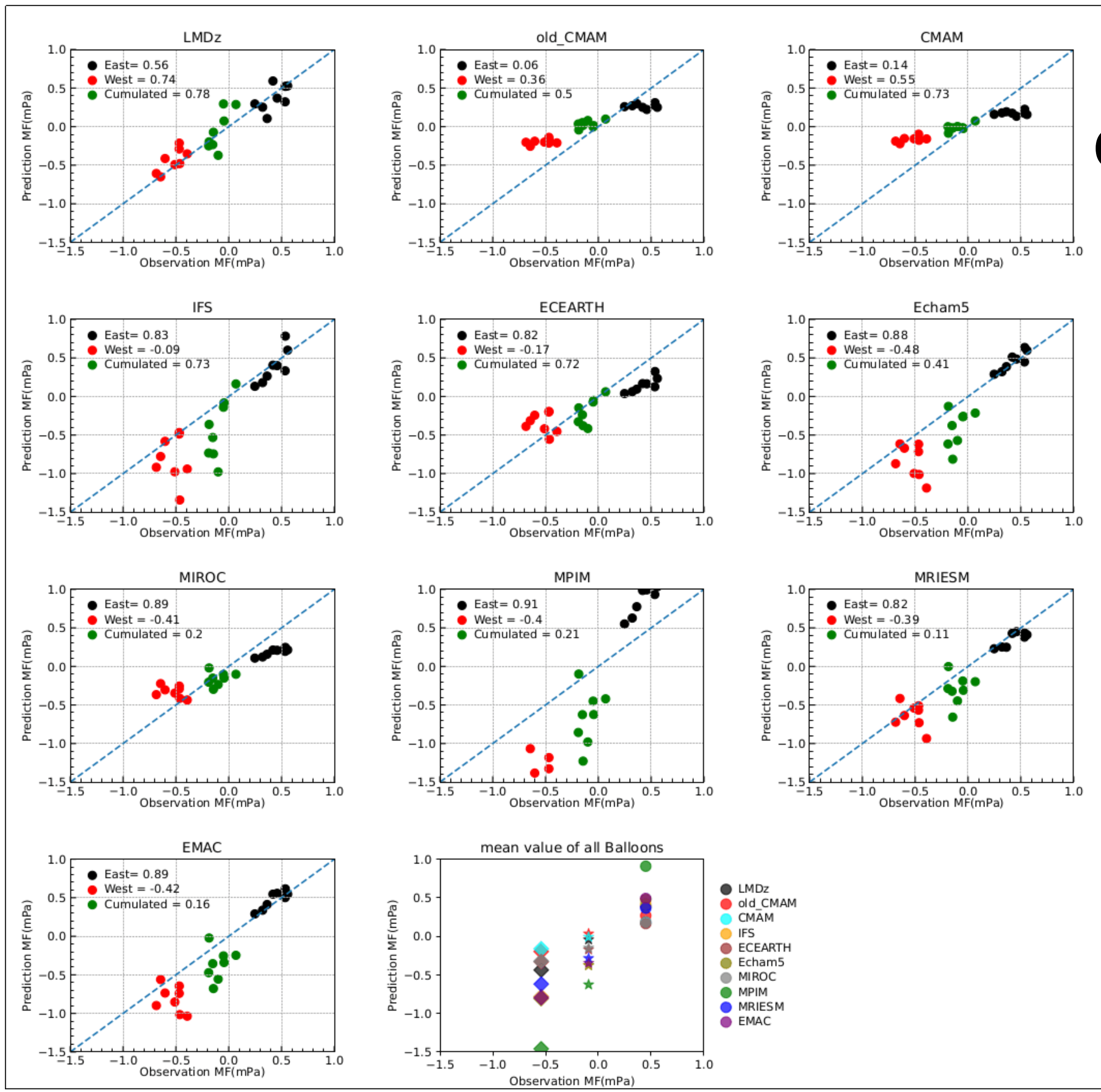
Convective gravity waves and the tropics : Strateole 2

LMDz6

CMAM

IFS

ECham5



Parameterization of GWs in large scale models
6) Perspectives

Take home message:

« We scientific are not fool »

Good example of theories verified by obs a posteriori

Perspective in terms of validation:

BAYESIAN estimate of parameters, including EnKF techniques?
Extent to Loon balloons
Extent to other GWs parameterization (frontal waves and mountain GWs)
Do improved schemes reduce model errors ?
Model tuning using uncertainty quantification (UQ)

Use of high resolution simul.s (DYAMON)
Use of Satellite observations that detect a fraction of the GW spectra (more global but coarser in resolution)

In terms of dynamics :

Interaction between the boudary layer and mountain gravity waves